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CLASSIFICATION OF COASTAL ENVIRONMENTS

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CRESCENTIC COASTAL LANDFORMS

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Charlottesville, Virginia 22903

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Crescentic coastal landforms

by

ROBERT DOLAN, LINWOOD VINCENT, and BRUCE HAYDEN
Charlottesville, Virginia

with 2 figures, 4 photos and 2 tables

Zusammenfassung. Die räumliche und zeitliche Dimension, die Topographie und das Prozeßgefüge bogenförmiger Küstenformen bilden den Rahmen für die Standardisierung der in der Literatur erscheinenden Terminologie. Zu diesen Formen gehören Spitzen, Hörner, Sandwellen, primäre und sekundäre Kapformen.

Summary. The spatial and temporal dimensionalities, as well as topographic and process associations of crescentic coastal landforms, are the context for standardization of terminology appearing in the literature. These forms include cusplets, cusps, sand waves, and secondary and primary capes.

Résumé. Au but de standardiser la terminologie, les auteurs s'intéressent aux formes côtières en croissant, en tenant compte non seulement de leurs dimensions dans le temps et dans l'espace mais aussi des relations entre les formes topographiques et les processus. Les formes considérées sont les croissants de plage, les cornes, les rides de sable et les caps de premier et de second ordre.

Introduction

Field and laboratory investigations of the past several years have established the importance of understanding the processes responsible for crescentic landforms along sandy coasts (DOLAN & FERM [1968], LONGUET-HIGGINS & PARKIN [1962], DOLAN [1971], HOM-MA & SONU [1962], BOWEN & INMAN [1971], KOMAR [1971], and BAKKER [1968]). Although results of this research have explained some of the specific relationships between the configuration of beach deposits and the processes associated with wave transformation, the terminology that has developed in the geologic literature and through common usage has resulted in misunderstanding and difficulties of communication. This is a problem

not uncommon in geomorphology, in which most of our terminology can be traced to descriptive rather than genetic roots.

In this paper we will (1) summarize, from the literature, the most commonly used terms for crescentic coastal landforms and (2) review relationships between these forms, inshore processes, and characteristics of the beach deposit.

Literature Review

Interest in crescentic coastal landforms is found in the earth science literature as early as 1834, primarily focused on the description of beach cusps and associated processes. By the 1890's, descriptions had extended to cuspate forelands. Johnson (1919) and Evans (1938) provided the first classifications of these features. Recent research has focused on further elucidation of the relationship between process and form.

In our review of the literature, the crescentic coastal landforms have been divided into three groups: (1) cusplets and cusps; (2) sand waves; and (3) cuspate forelands, including capes and secondary capes. The primary authors for the period 1834 to 1972 are listed, in chronological order, in Table 1.

Several nineteenth-century geologists investigated the origin of smaller cuspate features. Palmer (1834) first described ridge and furrows on the beach face, noting their erosional channel development when longshore drift was absent. Various authors (Shaler 1894, Gulliver 1896, Cornish 1898, Jefferson 1899, Branner 1900, and Wilson 1904) examined cusp spacing and form, suggesting that erosive processes were resonsible in their formation. Johnson

Table 1 — The Literature

Cusplets	Wilson (1904)	Evans (1938)
	Johnson (1919)	Dolan & Ferm (1968)
Cusps	Palmer (1834)	Boye (1954)
	Shaler (1894)	Smith & Dolan (1960)
	Gulliver (1896)	Longuet-Higgins (1962)
	Cornish (1898)	Shepard (1963)
	Jefferson (1899)	Otvos (1964)
	Branner (1900)	Yasso (1964)
	Wilson (1904)	Ottmann (1965)
	Johnson (1910, 1919)	Russell & McIntire (1965)
	Shepard (1935, 1938)	Cloud (1966)
	Evans (1938, 1939, 1941, 1945)	Zenkovich (1967)
	Kuenen (1948)	Dolan & Ferm (1968)
	Guilcher (1949)	Bruggeman (1971)
Sand Waves	Bruun (1954)	Bakker & Joustra (1971)
	Hom-ma & Sonu (1962)	Dolan (1971)
	Bakker (1968)	Bowen & Inman (1971)
	Dolan & Ferm (1968)	Komar (1971)
Capes and Secondary Capes	Abbe (1895)	White (1966)
	Gulliver (1896)	Zenkovich (1967)
	Cornish (1898)	Dolan & Ferm (1968)
	Johnson (1919)	Hoyt & Henry (1971)
	Shepard (1963)	

(1910, 1919) thoroughly reviewed the literature on the geomorphology of cusps and most other beach features. He proposed that cusps originated by differential erosion of random depressions on the beach face. SHEPARD (1935) noted the influence of tidal cycles in the construction and destruction of these features.

No formal classification of beach cusps was attempted until 1938. EVANS (1938) stratified cusps into five categories: (1) capelike storm cusps, (2) large cusps with subaqueous apex ridges, (3) cusps due to erosion and deposition caused by an obstruction (4), very small cusplets; and (5) ideal beach cusps. He (1938, 1939, 1941, 1945) observed that ideal cusp formation (type 5) was preceded by building of a bermlike ridge which was then breached, but noted that this might not be true for all cusp features.

BAGNOLD (1940) and KUENEN (1948) emphasized lateral movement of material (though in opposite directions) in the formation of cusps. The dependence upon waves and tides has been explored by SHEPARD (1935), KRUMBEIN (1944), SCHUPP (1953), and LONGUETT-HIGGINS & PARKIN (1962). Observations and descriptions of the features and associated processes have been reported by several field investigators (GUILCHER 1949, BOYE 1954, SMITH & DOLAN 1960, SHEPARD 1963, OTVOS 1964, YASSO 1964, OTTMANN 1965, RUSSELL & MCINTIRE 1965, and ZENKOVICH 1967), further elucidating the erosional and depositional origin of these features.

Although there is considerable literature on cusp form, few explanations linking form to fluid processes have been advanced. CLOUD (1966) suggested an application of Plateau's rule. BOYE's (1954) observations indicated that cusps form sequentially, and that this might imply a lack of rhythmical cause. In their investigation of rip currents, BOWEN & INMAN (1971) suggested that beach cusps could be associated with edgewaves.

The existence of medium-scale (10^2 to 10^3 meters) sand waves (or shoreline rhythms) was not generally recognized until after 1950. This was the result, in part, of lack of suitable observational data sets. EVANS (1938), from studies on the Great Lakes, did discuss storm cusps as being large, capelike cusps deposited during a storm. SHEPARD (1963) remarked that giant storm cusps were found both as separate features and in groups. He associated these features with back eddies in the longshore currents. KOMAR (1971) investigated the connection between rip current cells and giant cusps, and BOWEN & INMAN (1971) proposed that giant cusps and crescentic bars are caused by edgewaves.

BRUUN (1954) noted that bottom features of the Dutch coast had series of migrating rhythmic features and HOM-MA & SONU (1962) connected offshore sequences of rhythmic bars with the subaerial longshore beach rhythms. BAKKER & JOUSTRA (1971), from studies of historical shoreline change in the Netherlands, found wavelike trends of erosion and deposition along the coast. BAKKER (1968) proposed a wave-form theory for sand waves.

DOLAN & FERM (1968) linked these features into a hierarchical system of crescentic landforms. BRUGGEMAN (1971) found smaller beach cusps superimposed upon the large (10^3 order) cusplike sand waves, which provides some verification of DOLAN's theory.

Capes and secondary capes, including cuspate forelands, have a long history of interest to geologists. SHALER (1894) implied that tides were respon-

sible for their formation. ABBE (1895), GULLIVER (1896), and CORNISH (1898) recognized the prominence of the larger capes, relegating their cause to the action of tides and currents. ABBE proposed back-set eddies of the Gulf Stream as a cause for the Carolina Capes. GULLIVER extended this to three possible pairs of back-set eddy-current motions. WILSON (1904) discussed the formation of cuspate forelands on lakes.

JOHNSON (1919) classified cuspate forelands into three groups: (1) simple cuspate forelands (parallel ridge and swales to both sides of the foreland), (2) truncated cuspate foreland (erosion of simple forelands) and (3) complex cuspate forelands (progradation of truncated foreland). JOHNSON, however, presented no definite theory for their origin.

KING (1959) emphasized the longshore movement of material into spits that tended to parallel the dominant wave direction. She also noted that the meeting of two barriers also builds a cuspate foreland.

SHEPARD (1963) recognized two types of cuspate forelands. The first is the simple cuspate foreland of JOHNSON, the second the truncated cuspate foreland. He summarized four theories for formation of those features along the east coast of the United States: sediment load greater than capacity of currents, offshore shoal-induced wave deflection, eddies in the Gulf Stream, and unidirectional flow of sediment.

ZENKOVICH (1967), in summarizing accumulative shoreline forms, noted that cuspate forelands resulted from a combination of wave direction and supply of sediment. Both ZENKOVICH (1967) and SHEPARD (1963) considered cuspate spits on both seacoast and lagoon shores.

DOLAN & FERM (1968) nested these features within a system of crescentic landforms of differing scales. They classified foreland features into capes and secondary capes. The differentiating criterion for classification was the spacing of the feature along the coast. Cape spacing was of the order of 10^5 m, secondary cape spacing was of the order of 10^4 m.

WHITE (1966) and HOYT & HENRY (1971) emphasized the geologic history of the Carolina capes. WHITE noted that the present-day capes were part of a sequence of cape features that have moved out to sea and inland with changes in sea level caused by Pleistocene glaciation, while HOYT & HENRY (1971) considered the capes as dependent upon river-mouth shoals.

Relationships between form, processes, and beach characteristics

The natural stratification of crescentic coastal landforms by size, temporal span, topographic association, and relative formative process as described in the literature is presented in Table 2. Five categories are recognized: cusplets, cusps, sand waves, secondary capes, and primary capes.

This natural structuring has an apparent hierarchy (Fig. 1 and Fig. 2) which distinctively separates the features, but allows for contemporaneous occurrence. Thus, the time scales for these features increase from minutes for cusplets to centuries for capes, and the size increases from meters to hundreds of kilometers. Cusplets are features of the beach step, cusps are erosional features of the berm,

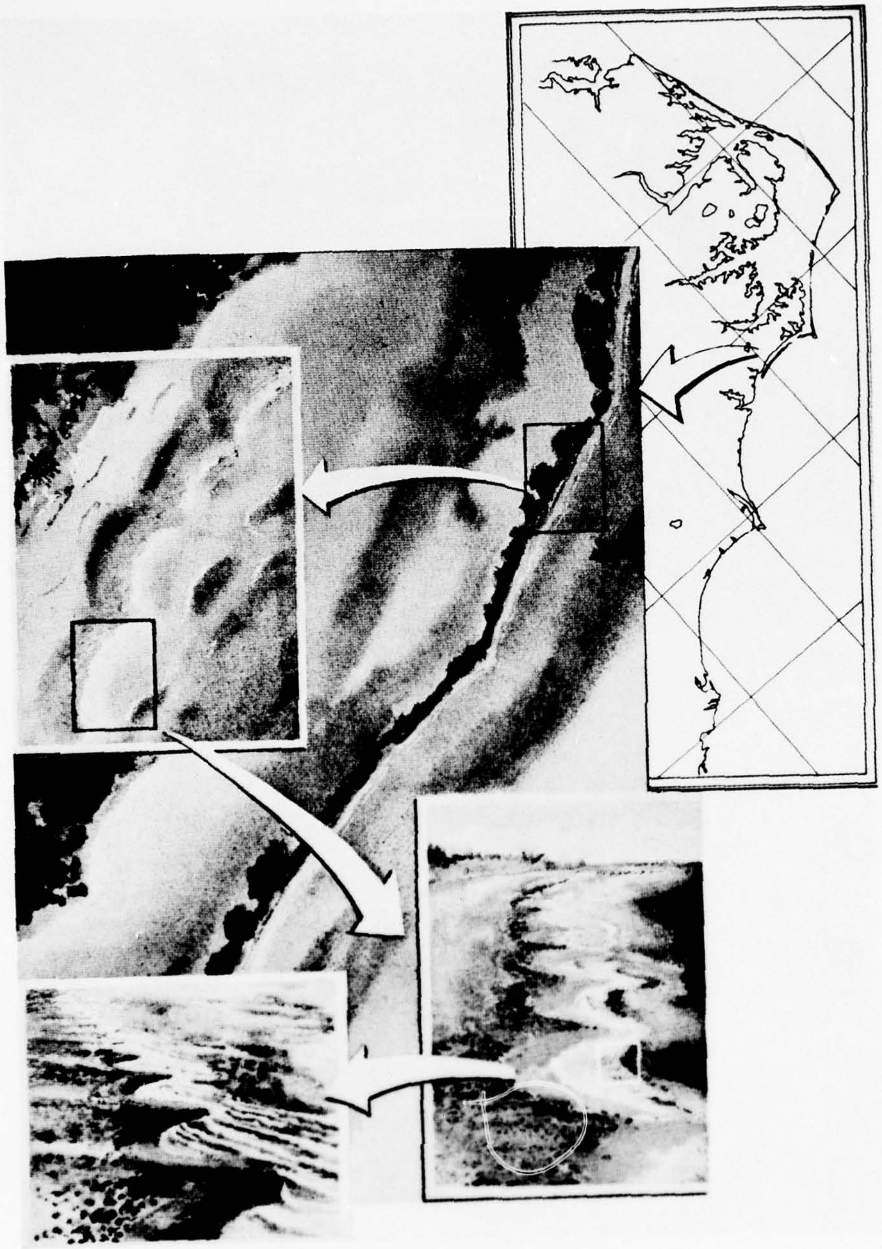

Fig. 1. Hierarchies of coastal features.

Photo 1. Cusplets.

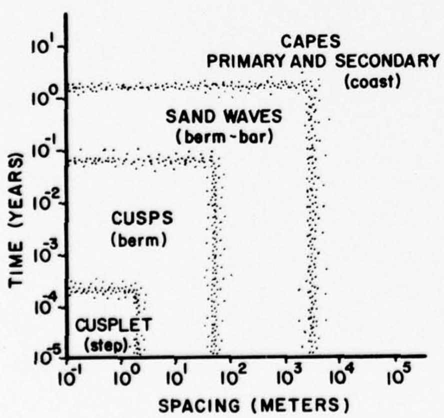

Fig. 2. Spacing and time characteristics for crescentic features.

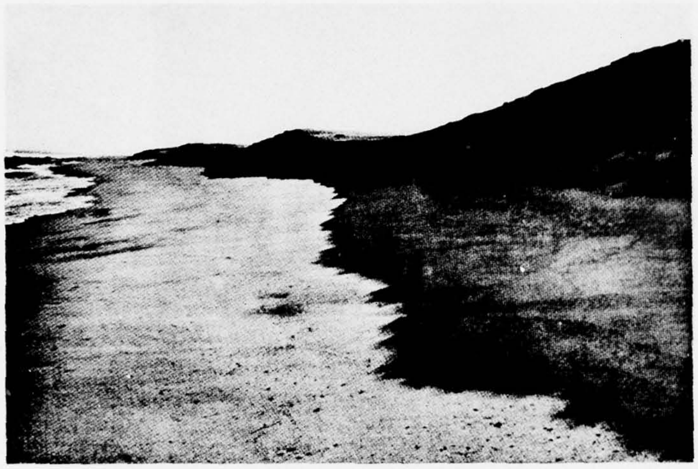

Photo 2. Cusps truncated by erosion. The stratigraphy indicates their erosional development.

Photo 3. Sand waves at Cape Hatteras, North Carolina.

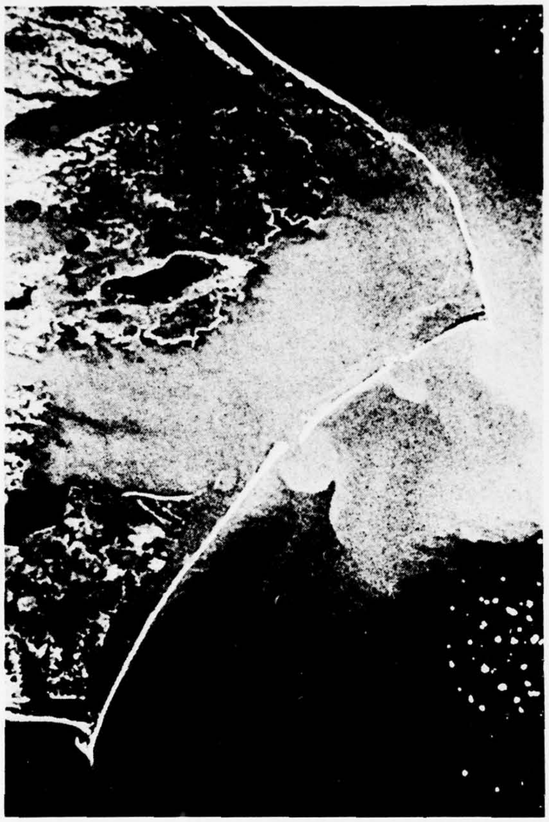

Photo 4. Primary and secondary capes in North Carolina (NASA-Apollo 9).

sand waves are complex deposits of the berm-bar system, and capes are manifestations of the long-term equilibrium of sediment distribution and energy gradients in the coastal system, as influenced by regional geology. The processes responsible for the landforms range from swash action to confluence of large-scale coastal currents. The literature does not indicate any consistent characteristic material size or tidal associations.

Cusplets

Cusplets are geomorphic features of the beach step, rhythmic in the longshore direction, consisting of small, erosional channels or grooves formed by swash and backwash flow (Photo 1). Their temporal span ranges from minutes to hours.

Table 2 Crescentic landforms

Form Characteristic	Cusplet	Cusp	Sand Waves	Secondary Capes	Primary Capes
Spacing	0 to 3 m	3 to 30 m	100 to 3000 m	1 to 100 km	200 km
Material	Fine Sand-Gravel	Sand-Boulders	Sand	Sand	Sand-Gravel
Topographic Association	Step	Berm, Beach Face	Beach Berm-Offshore Bar System	Coastal Plains; Shores with Sufficient Sediment	Coastal Plain Deltas
Rhythmicity	Yes	Yes	Yes	Often	Not Always
Motion	Fixed	Normal to Beach	Downdrift	Probably Downdrift	Slow Downdrift
Temporal	Minutes to Hours	Hours to Days	Weeks to Years	Decades	Centuries
Suggested Processes	Swash action on beach face. Groove erosion.	Berm deposition and erosion.	Wave action, nearshore circulation cells, back eddies of longshore transport currents.	Kinematic nature of sediment transport, circulation cells.	Wave action, confluence of coastal currents, back-set eddies, and shoals.

Cusplets are found on beaches with grain sizes ranging from fine sand to gravel, with spacing up to 3 m. In general they tend to form under low-energy conditions, and once formed remain in place. Rarely do they last longer than one tidal cycle.

Cusps

Cusps are features of the beach face (berm), rhythmic in the longshore direction, consisting of small shallow sloped bays in the berm, separated by more steeply sloped horns (Photo 2). They are formed by swash action and currents of a newly deposited berm (although the exact method of formation is uncertain). Their time scale is from hours to days.

Cusps range in length (horn to horn) from 3 to 30 m, in width from 1 to 10 m, and in height up to 2 m. They have been observed on beaches with grain sizes of from fine sand to boulders and are believed to form when there is a drop in the energy level of the sea (as after a storm) or on the falling tide. Cusps do not migrate in the longshore direction, but the forms can move across the beach.

Sand Waves

Sand waves are part of the beach-bar-trough system, rhythmic in the longshore direction, consisting of a gentle, crescentic or wavelike shape of the shore-

line. Sand waves are associated with the dynamics of the longshore transport system (Photo 3). However, various authors have suggested a wide range of processes for their formation ,including near-shore circulation cells, edge waves, and kinematics of a flowing mass of sediment. Their life span ranges from weeks to years.

Sand waves are found mainly on sand coasts where lengths of 100 m to 3 km have been reported. They have been observed to migrate alongshore. Shoreline rhythms or sand waves have also been termed giant cusps or storm cusps.

Sedimentary Capes

Capes are features of sedimentary coasts, consisting of convex, commonly cuspate promontories spaced from 100 to more than 200 km apart (Photo 4). They are formed by the action of waves on shoals, confluence of coastal currents, or deltaic deposition. Material sizes range from sand size through cobble size.

Most capes are products of the post-Wisconsin, usually 5,000 years or older, and many have undergone erosion and depositional cycles, resulting in change of form and position.

Sedimentary capes may be further divided into two subgroups: primary capes with a spacing of 200 km and secondary capes (or false capes) with spacing of 100 km. Their areal extent likewise decreases. Complicating the definition of capelike features is the possibility that secondary capes (or false capes) may be erosional remnants of primary capes.

Conclusion

The natural nesting of the temporal and spatial scales and topographic occurrence of crescentic coastal landforms provides a strong context for their investigation. This nesting of scales and association implies that the features themselves may be hierarchical, and that these landforms are products of superposition of processes of different scales of motion which act contemporaneously in time and space. Although the features can occur simultaneously, often they do not. Depending upon the characteristics of the beach sediment and the particular energy conditions, any combination may be found at any time.

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13. ABSTRACT

The spatial and temporal dimensionalities, as well as topographic and process associations of crescentic coastal landforms, are the context for standardization of terminology appearing in the literature. These forms include cusplets, cusps, sand waves, and secondary and primary capes. (U)

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Technical Report No. 14

CLASSIFICATION OF COASTAL LANDFORMS OF THE AMERICAS

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Charlottesville, Virginia 22903

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Classification of coastal landforms of the Americas

by

R. Dolan, B. Hayden and M. Vincent, Charlottesville, Virginia

with 6 figures and 4 tables

Zusammenfassung. Eine neue beschreibende Klassifikation von Küstenformen, die von der Lithologie im Küstenbereich, von der Topographie und den Strandtypen ausgeht, wird vorgestellt und auf die Küsten beider Amerika im Maßstab 1 : 20 Mill. angewandt. Die hemisphärische Symmetrie und Abweichungen von ihr in Bezug auf die Unterteilung der Relieftypen werden untersucht und Unterschiede zwischen Nord- und Südamerika festgestellt. Die Beziehungen zwischen den Strandlinienelementen und dem küstennahen Wellenregime werden untersucht und die Zusammenhänge zwischen Wellenregime und den stärker dynamischen Reliefelementen dargestellt. Im einzelnen wurde festgestellt, daß Korallen- und Mangroveküsten nicht in Regionen mit großer Wellenenergie vorkommen. Über 50 % der erfaßten Korallen- und Mangrovenbereiche liegen in Gebieten mit mäßiger Wellenenergie. Marsch- und Wattenküsten sind fast ausschließlich auf Gebiete mit sehr niedrigen Wellen beschränkt. Sandstrände und Nehrungen werden ganz überwiegend in Gebieten mäßiger Wellenenergie angetroffen. In den Gebieten mit höchster Wellenenergie herrschen bogenförmig-konkave Strandlinien sowie Sandstrände neben felsigen Kaps vor.

Summary. A new descriptive classification of coastal landforms based upon coastal lithology, topography, and shoreline type is presented with application to the coastal areas of the Americas on a scale of 1 : 20,000,000. Hemispheric symmetry and departures from symmetry in the distribution of landform types are examined, and differences between North and South America are noted. The relationships between shoreline characteristics and coastal wave climates are analyzed, and the wave climate dependency for the more dynamic landform types is presented. Specifically, coral and mangrove shorelines were not found to occur in high wave-energy regions, and more than 50 % of recorded occurrences were in areas of moderate wave energies. Marsh and mudflat shorelines were almost exclusively restricted to areas of very low waves. Sand beaches and barrier islands were found pre-eminently in areas of moderate wave energies. In areas of highest wave energies, pocket beaches and sand beaches with rock headland dominate.

Résumé. Une nouvelle classification descriptive des formes côtières basée sur la lithologie, la topographie et le type de rivage est présentée; elle est accompagnée de son application aux

LANDFORM LEGEND

To Figures 1, 2 and 3 on page 72 and 80

GEOLOGY

- LOW RESISTANT
- OLDER RESISTANT
- RECENT VOLCANIC
- RECENT FLUVIAL & DELTAIC
- GLACIAL & GLACIAL FLUVIAL

RELIEF

- HIGH RELIEF
- HIGH RELIEF - CLIFFED
- LOW RELIEF
- LOW RELIEF - CLIFFED
- COASTAL PLAIN
- COASTAL PLAIN - CLIFFED

SHORELINE CHARACTER

- SAND BEACH OR BARRIER ISL.
- SAND BEACH - ROCK HEADLAND
- POCKET BEACH
- MUDFLAT OR MARSH
- SWAMP OR MANGROVE
- CORAL
- ROCK

to page 72

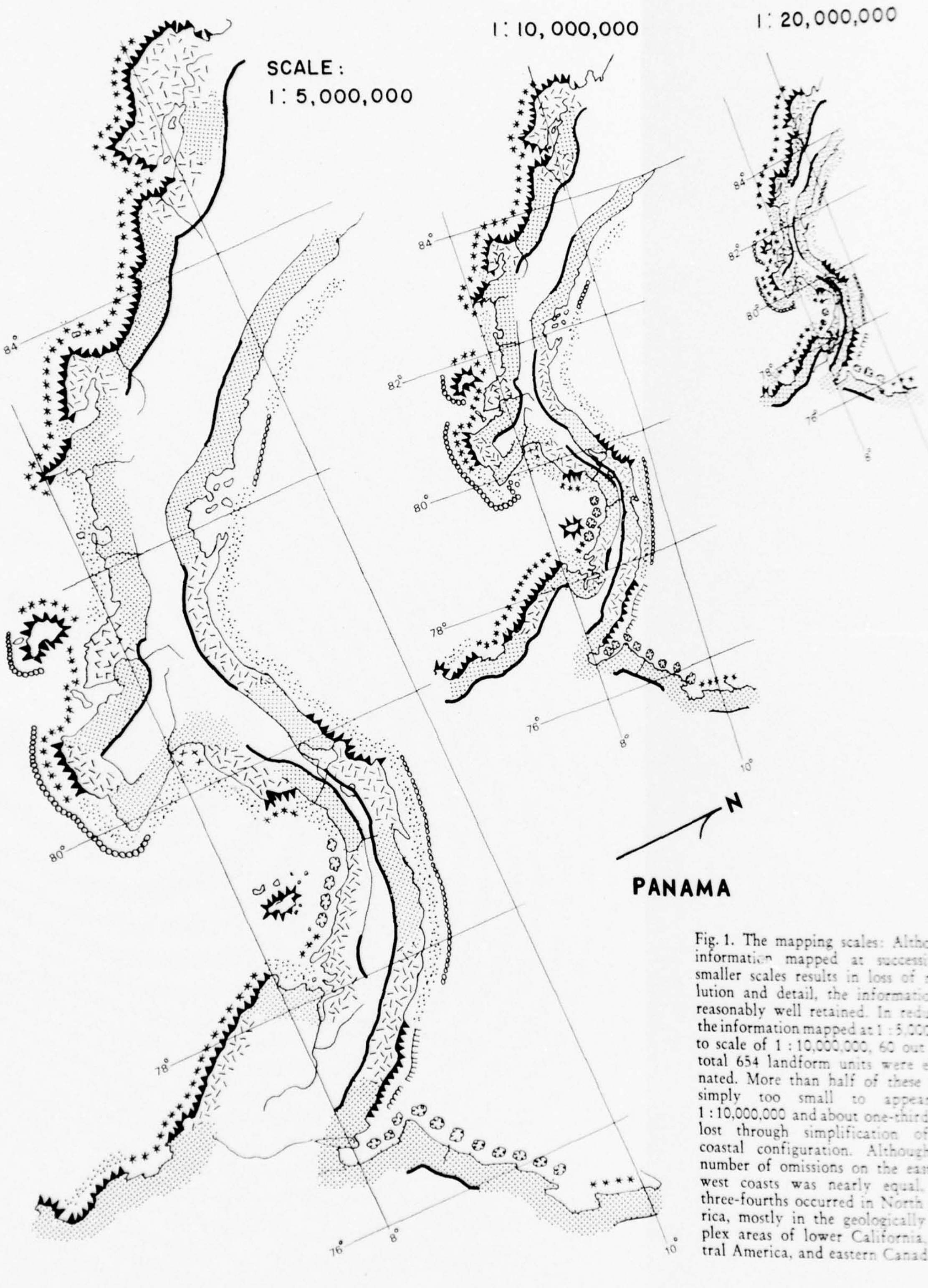

Fig. 1. The mapping scales: Although information mapped at successively smaller scales results in loss of resolution and detail, the information is reasonably well retained. In reducing the information mapped at 1 : 5,000,000 to scale of 1 : 10,000,000, 60 out of a total 654 landform units were eliminated. More than half of these were simply too small to appear at 1 : 10,000,000 and about one-third were lost through simplification of the coastal configuration. Although the number of omissions on the east and west coasts was nearly equal, over three-fourths occurred in North America, mostly in the geologically complex areas of lower California, Central America, and eastern Canada.

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régions côtières des Amériques à l'échelle du 1 : 20 000 000. La symétrie hémisphérique et les écarts à la symétrie dans la distribution des types de formes sont examinés et des différences entre l'Amérique du Nord et du Sud sont notées. Les relations entre les caractéristiques du rivage et les climats côtiers sont analysées; les types de morphologie côtière les plus dynamiques sont effectivement contrôlés par le climat, car celui-ci détermine l'importance des vagues Spécifiquement, les rivages de coraux et de mangroves ne se trouvent pas dans les régions où les vagues ont une haute énergie; plus de 50 % des formes de ce type qui ont été observées, se trouvent dans des régions où l'énergie des vagues est modérée. Les lignes de rivage marécageuses et boueuses sont presque exclusivement réparties dans des régions où l'action des vagues est très réduite. Les plages de sable et les îles de barriès sont localisées avant tout dans des régions où l'énergie des vagues est modérée. Dans les régions où l'action des vagues est la plus grande, de petites plages de sable alternent avec des promontoires rocheux.

Introduction

For more than a century, geologists and geomorphologists have been concerned with developing a widely applicable classification of coastal landforms. Since the mid-1800s, more than twenty classifications have been published. Some of the discipline's most distinguished members are among the contributors; and, at the time of his death, R. J. RUSSELL was considering a new classification based upon his extensive field observations[1].

With this rich literature, is there a need for another classification? When the senior author of this paper agreed to map the coastal landforms of the United States for the U. S. Geological Survey *National Atlas* (DOLAN 1970), he thought the answer would surely be negative. However, following a review of the existing classifications, we agreed with MCGILL (1959) who pointed out that:

The development of a classification is a mental challenge, a stimulating problem mainly in deductive reasoning, whereas application of the new scheme to the mapping of the world's coasts is regarded by many as physical drudgery, and hence a much less popular undertaking.

Classifications are numerous, yet there are few examples of application.

The objective of the *National Atlas* mapping was to provide as much information as possible about the coasts of the United States at a scale of 1 : 7,500,000 while omitting the detail presented within the other thematic maps of the Atlas. Existing coastal classifications were inappropriate: most are either too detailed, demanding complex or non-existing data, or too simple even for a scale of 1 : 7,500,000.

A second and more comprehensive program of mapping coastal phenomena was begun by the authors in 1971, under the sponsorship of the Geography Programs, Office of Naval Research. The objective was to determine whether or not the energy and mass transfer systems within the coastal zone can serve as a basis to systematize coastal information. With the use of a modified version of the original *National Atlas* classification, the Americas were mapped at a scale

[1] It is interesting to note that RUSSELL closed his book, *River Plains and Sea Coasts* (University of California Press, Berkeley, 173 p.) in 1967 with this statement: "I regard geomorphology as an exciting science in its infancy, not as one about which so much is known that it is profitable to sit in an office engaging in the proposal of classification of landforms."

of 1 : 5,000,000 to provide detailed data on coastal landforms. Since the 1 : 5,000,000 sheets measure 101.6 cm × 152.4 cm, the maps accompanying this paper are reduced to a less awkward size at a scale of 1 : 20,000,000 (South-America) and 1 : 25,000,000 (North-America).

Literature

The earliest published classification yet discovered appeared in 1827 in an Encyclopedia of Geography by MALTE-BRUN (1827). Brief and sketchy, it listed such descriptive categories as steep, broken, hilly, low, flat, and indented coasts and gave an example with a genetic-focused text.

In 1876, PESCHEL presented one of the first formal discussions of coastal geomorphology, and ten years later RICHTHOFEN introduced the first scientific systematization of coastal landforms[2]. The classifications which have since appeared are diverse in approach but can be categorized as either genetic or descriptive.

None of the classifications have proved satisfactory on a world-wide basis because data and information are inconsistent and frequently lacking. Definitions of basic terms are weak or non-existent, and there are disagreements as to which of the many coastal elements should be used in classification. However, most researchers agree that genetic classifications are scientifically desirable, but the descriptive systems are favored in practical application.

The RICHTHOFEN classification of 1886, which described coasts in terms of structural trend, shoreline configuration, and presence of cliffs, strongly influenced subsequent work. Elements of it were adopted or modified by SUESS (1888), PENCK (1894), DAVIS (1898), DE MARTONNE (1909), and COTTON (1918). With GULLIVER (1899) and DAVIS (1912), genetic systems began to replace the descriptive systems. In their consideration of coasts formed by the elevation or lowering of continents, the concept of the geomorphic cycle and the changing base level was introduced. JOHNSON (1940) was concerned with the most recent change in base level, so he not only adopted the two-part Davisian scheme, but expanded it to include four categories: coasts formed by submergence, emergence, a combination (compound), or neither (neutral). Though more refined, differentiation between coastal types was still inadequate since nearly all were typed as compound.

JOHNSON's scheme and the Davisian cyclic concept were widely accepted theories in coastal morphology for many years. In fact, they were so entrenched that the hesitancy to acknowledge new concepts retarded progress in coastal studies. For example, the next major classification system to appear in literature (SHEPARD 1937) was strongly criticized for its introduction of the concept of glacial control on sea level (LUCKE 1938; SHEPARD 1937 and 1938). The growing knowledge that coasts had undergone both submergence and emergence during the Holocene rendered JOHNSON's system functionless.

[2] In one discussion (VOGEL 1966) of the history of coastal classification, it is stated that RICHTHOFEN had a shoreline classification as early as 1866. However, no other discussion known to us dated RICHTHOFEN earlier than 1886. Although he may have devised a classificatory scheme in 1866, none appears to have been published until 1886.

Major divisions of the SHEPARD classification distinguished coasts by dominant development process and development stage: Youthful coasts formed mainly by terrestrial processes and mature coasts modified mainly by marine processes. A hybrid system, the classification extended the work of DAVIS and JOHNSON. Although genetic, the elements of some of the subdivisions are mostly descriptive (delta coast, mangrove coast, etc.). SHEPARD had hoped to show that coastal origin and history could be determined by nautical charts and photos. While the classification failed in this attempt, it did prove to be extremely useful in studying coasts from charts and photos.

Focusing on base-level change in the tradition of JOHNSON, COTTON (1918, 1942, 1952, and 1954 b) devised several dichotomous genetic classificatory schemes, each of which modified and added to his earlier systems. The 1952 scheme was based on stable and mobile coast regions with subdivisions of submergence and emergence. Widespread application of the COTTON systems is questionable because they were devised largely on a basis of New Zealand coastal types. A further disadvantage is the inclusion of the geomorphic-cycle concept, which has been applied in other landform classifications with little success.

In 1952 VALENTIN introduced a new theory concerning base-level changes and the Davisian geographical cycle. He recognized the importance of marine processes and suggested that horizontal advance and retreat is as important as submergence and emergence. The VALENTIN system then was two-fold: Coasts were classified by configurations resulting from past processes and by the type of the present coastal dynamics. This approach eliminated the problem of JOHNSON's overly large "compound coast" category. In his goal of providing an explanation rather than a description of coasts, VALENTIN's "Die Kuesten der Erde" stood as the most comprehensive attempt at a genetic classification (also see VALENTIN 1972 a and 1972 b). However, the classification fell prone to the problems inherent in genetic systems: The lack of adequate information.

Although most of the classifications that appeared in the 1950's were geographically restricted in scope, their methods and ideas were nevertheless important. The system conceived by FLEMING & ELLIOTT (1956) was significant because it considered several variables in the context of a marine environment[3]. Like COTTON, PRICE formulated several classifications. His 1954 genetic classification of coastal types of the Gulf of Mexico was similar to the FLEMING & ELLIOT system; yet, in the treatment of geologic structure, it followed the tradition of RICHTHOFEN & SUESS. The major interest of this system was its introduction of numerical symbols to codify coastal types. The TANNER classification of 1958 was basically descriptive and localized; however, it represented an important attempt to describe relationships between bedrock, materials in transit, energy levels, and geometric patterns.

McGILL's world coastal classification was a significant descriptive scheme, particularly since the system of landforms and shore features was presented in

[3] Although the FLEMING & ELLIOTT system was published in 1956, it was in manuscript form in 1950. Their work was significant to PRICE's as he stated: "FLEMING & ELLIOTT have made a beginning of an overall quantitative and qualitative oceanographic approach to the study of shorelines which is here revised, enlarged, and treated in greater detail in some of its aspects . . ." (PRICE 1954).

map form (McGill 1958). Although more difficult to read than Valentin's, McGill's maps were only a first approximation derived from a data base of small-scale topographic maps. The effort was part of a larger project to investigate aspects of coastal environments (Putnam et al. 1960).

Several Russian researchers devised classifications or discussed the problem, but for most there were translation difficulties. The classification compiled by Ionin et al. (1964) at the Institute of Oceanology appeared in map form and was discussed by Zenkovitch (1967 a). Although recognizing the obstacles of mapping a genetic scheme on a world-wide scale, the work tried to indicate the basic relief-forming processes. The classification was based on factors of marine processes and considered development state, while geologic structure and types of vertical movement were not considered as classificatory elements[4].

Alexander's classification of 1962, though localized, was similar to McGill's both in its descriptive nature and the presentation of results in map form. Alexander worked on much larger scale maps and classified according to detailed shore form, such as vertical profile and shore outline, rather than by landform type. The Alexander system more satisfactorily described and classified shorelines and was easier to apply than McGill's, yet it was suitable only for detailed mapping. To map the world's coasts according to Alexander's classification would require several hundred maps.

Continuing the interest in marine processes begun by Valentin and then extended by Fleming & Elliott, Price & Tanner (1960), the classification by Davies (1964) described the world shorelines in terms of storm waves, swell, and energy environments. Although the ideas were not entirely new, they did focus attention on wave and tidal activity and did further demonstrate that classifications which did not consider the effects of marine processes failed to recognize some of the most important factors in the coastal environment.

The Ottmann classification (1962 and 1965) was a simplistic scheme primarily concerned with topographic relations between the coastal area and the continental shelf. The coast types were distinguished by relief, structure, and configuration. A scheme similar to that of Valentin, although devised to fit local conditions, was proposed by Swan in 1967 and 1968; it distinguished between prograded and retrograded coasts. The system questioned the validity of the cyclic concept stating that coastal development was the result of several complex factors.

In 1969, Odum introduced an ecological classification of coastal systems of the United States based on the processes which dominate the functional activity of the system. As a classification concerned with dominant energy flows, it was the first to deal with many biological, chemical, and physical stress elements of coastal areas in a systematic way. In addition, it considered the stress influence of man's activities on the coastal environment. Although estuarine areas were the object, the work presented concepts which could have interesting results if applied to all coasts.

[4] Mention of other Russian coastal classification schemes is given by Zenkovitch (1967 b : 383–447).

The final classification of importance was that of INMAN & NORDSTROM (1971). Athough genetic, it includes strong descriptive elements. Stimulated by the explosion of theories and data on continental drift, the classification attempted to discover a system of variations in world morphology as related to moving tectonic plates. Like VALENTIN, the classification was concerned with past land movements as well as present marine dynamics. INMAN & NORDSTROM introduced two important concepts to coastal classification:

1. The extent of coastal features should be statistically analyzed as well as presented in map form;
2. The scale problems of McGILL and ALEXANDER can be overcome by systematizing coasts as to levels or orders of coastal features.

Classification of Coastal Landforms of the Americas

The configuration of any coastal region can be described in terms of four fundamental factors:

1. Lithology of the materials exposed along the coast;
2. Configuration or attitude of the materials;
3. Intensity of the coastal processes;
4. Stability of the land-sea interface.

Since most of the coasts underwent submergence during the late-Wisconsin time and since our detailed knowledge of coastal processes is limited to a few areas, we focused on the attributes, lithology, and configuration. Therefore the classification is almost purely descriptive. In 1967, RUSSELL stated:

"Were I to forecast the basis upon which a sound classification of shorelines might be based, I would first think in terms of lithology. Crystalline rock coasts, for example, exhibit striking similarities, regardless of climatic, vegetational, or other environmental contrasts".

We agree lithology and topography best describe the nature of coastal landforms; and when coupled with descriptions of specific shoreline types, such as deltas, fiords, and barrier islands, the serious student of landforms can easily reach conclusions concerning process-response relationships.

In mapping the Americas, three scales were used (fig. 1):

1. A scale of 1 : 5,000,000 for base-line data required in our analysis of coastal environments;
2. Scales of 1 : 7,500,000 and 1 : 10,000,000 for establishing regional patterns.
3. Scale of 1 : 20,000,000 for showing relationships between the continents.

Data

The selection and justification of the attributes discussed in the previous section are simple enough conceptually, but actual mapping is not an easy task. The primary problems are the availability of data and their consistency. Several data sources were used (table 1) in compiling the landform maps according to the devised classification system.

1. Geologic material (lithology) was the first element to be mapped. Although detailed information is presented on some of the geologic maps, there are difficulties in determining rock types because many of the source maps emphasize chronology.

2. For decisions concerning relief, topographic sheets at 1 : 250,000 were preferred; however, for South America and parts of Mexico, 1 : 1,000,000 was the largest scale map available. A 30.48-m (100-ft) contour interval is presented on most 1 : 250,000 maps, but the interval on the smaller scale maps was both larger and variable. For example, aeronautical charts have a 305-m (1,000-ft) contour interval while the 1301 USARMTOPCOM series contour interval varies around 91-m (300-ft). It was impossible, then, with 1 : 1,000,000 maps to make decisions equivalent to those made with 1 : 250,000 maps. In this case, information from Sailing Directions and Nautical Charts was used extensively.

Table 1 Data Sources

Elements of Classification		Data Source
Geology	Maps:	1. Carte géologique de l'Amérique du Sud (1 : 5,000,000) Commission de la Carte Géologique du Monde, Rio de Janeiro, 1963. 2. Geologic Map of North America (1 : 5,000,000). U. S. Geol. Survey, Washington, 1965.
	Books:	1. Handbook of South American Geology, W. F. Jenks, Geological Soc. America, Mem. Nr. 65, 1956. 2. Primary Literature (Journals and Reports).
Relief	Maps:	1. Topographic Maps of Canada, (1 : 250,000 series) Dept. Energy, Mines and Resources, Ottawa. 2. Topographic Maps of U. S., (1 : 250,000 series). U. S. Geol. Survey. 3. Topographic Maps of Mexico as Available (Series 1501 at 1 : 250,000). U. S. Army Topographic Command. 4. Aeronautical Charts (1 : 1,000,000 series) for North and South America. U. S. Air Force, St. Louis, Missouri. 5. Hydrographic Charts, (various scales) for North and South America, U. S. Naval Oceanographic Office.
	Books:	1. Sailing Directions, volumes for Central and South America and Canada. U. S. Naval Oceanographic Office. 2. Pilot Charts, U. S. Coast and Geodetic Survey.
Shoreline Character	Maps:	1. Topographic Maps, op. cit. 2. Aeronautical Charts, op. cit. Sailing Directions, op. cit.

Table 2 Attributes of the Classification

Classificatory Attributes	Class	Subclass	Definition
Relief			Spatial configurations of topographic gradients in vicinity of coastal zone.
	High		30.48-m (100-ft) contour present within 6.4 km (4 miles) of coastline and generally parallel and adjacent to the coastline.
	Low		30.48-m (100-ft) contour farther than 6.4 km (4 miles) from coastline with contours either parallel to the coast or indicative of hilly features.
	Coastal Plain		30.48-m (100-ft) contour farther than 6.4 km (4 miles) inland with shallow topographic gradient in the interior region.
		Cliffed	Presence of contours immediately adjacent to the shoreline or as reported in Sailing Directions.
		Non-cliffed	Absence of steep topographic gradients at coastline.
Lithology			Dominant characteristics of rocks exposed along coast and their relative responsiveness to change.
	Older Resistant		Materials that respond slowly to coastal processes. Local and regional geology dominates. Few, if any, features associated with the late Wisconsin sea-level stand. Mostly older crystalline rocks.
	Low Resistant		Materials that respond rapidly to coastal processes. Predominantly poorly consolidated sedimentary rocks.
	Recent Volcanics		Extrusive volcanics.
	Fluvial & Deltaic		Deposits associated with the terminal area of fluvial transport.
	Glacial & Glaciofluvial		Glacial tills and glacial outwash.
Shoreline character			The dominant feature or associated features comprising a visually recognizable unit of the coastline.
	Sand Beach		Sand-beach interface uninterrupted by rocky points or headlands.
	Sand Beach with Rock Headlands		Sand-beach interface interrupted by rocky headlands with headland-to-headland spacing greater than 8 km (5 miles).
	Pocket Beaches		Sand-beach interface interrupted by headlands or points with spacing of headlands or points less than 8 km (5 miles).
	Rocky		Interface of resistant rock without a definable beach structure.
	Mudflats Marsh		Fine sediment coast of low topographic gradient usually dominated by grasses.
	Swamp Mangrove		Fine sediment coasts of low topographic gradient usually dominated by mangrove.
	Coral		Coasts of barrier or fringing reefs frequently fronting sand beaches or mangrove swamps.

3. Topographic sheets at 1 : 250,000 provided a variety of relatively detailed information about the shoreline which was easily translated for the landform map. Although a great deal of information was also available on the 1 : 1,000,000 scale, it was far from adequate. To compensate, coastal descriptions given in the Sailing Directions were used. Though extremely helpful and amazingly detailed, consistency was an obvious drawback. The Sailing Directions describe the prominent features for purposes of navigation. In the frequent cases where cultural features were more prominent than physical, the physical shore character was given little or no attention.

4. Finally, if map sources failed to provide adequate information, we turned to primary data in the literature.

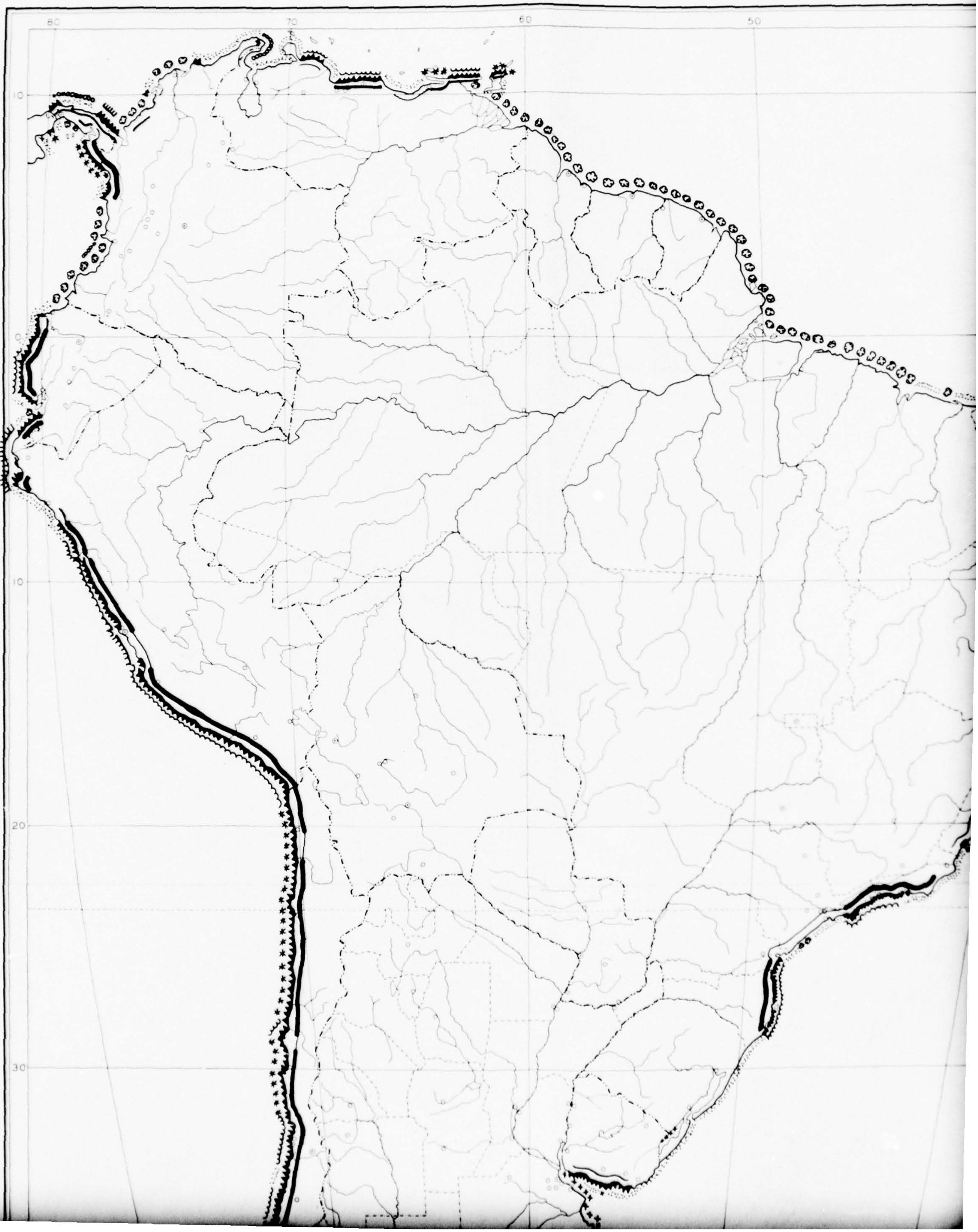
Maps

The spatial distributions of the three attributes mapped at a scale of 1 : 10,000,000 are presented in figures 2 and 3. The mapping of each attribute required decisions consistent with the definitions and subclasses presented in table 2.

In order to facilitate the analysis of the distribution of the coastal landforms of the Americas, the characteristics of each landform unit were coded on data cards. The information recorded for each unit included: geologic material, relief, shoreline type, continent, water body, nation, state codes, latitude and longitude of the midpoints of the unit, and the length of the unit in miles. The manner in which the length of the unit is found can significantly alter the predominance of landform types. The length used in the following analysis was determined by (1) first smoothing the coastline by eye at a scale of 1 : 1,000,000 (fig. 4) and (2) measuring the arc length between the endpoints of the landform unit. The data stored on the cards constitutes a matrix of coastal landform information.

Table 3 Shoreline Characteristics of North and South America

Total miles	(Percent) North America 51,862 (Percentages)	(Percent) South America 19,729 (Percentages)	Total miles	(Percent) North America 51,862 (Percentages)	(Percent) South America 19,729 (Percentages)
Cliffed	54 %	45 %	Recent fluvial and deltaic	2 %	8 %
High relief	37 %	27 %	Glaciofluvial	2 %	4 %
Low relief	15 %	15 %	Sand beach & barrier island	23 %	30 %
Coastal plain	2 %	3 %	Sand beach with rock headland	2 %	1 %
Non-cliffed	46 %	55 %	Pocket beaches	8 %	15 %
High relief	7 %	3 %	Rocky	37 %	20 %
Low relief	19 %	7 %	Mudflats marsh	29 %	4 %
Coastal plain	20 %	44 %	Swamp mangrove	2 %	26 %
Recent volcanic	4 %	1 %	Coral	1 %	3 %
Older resistant	66 %	34 %			
Low resistant	26 %	54 %			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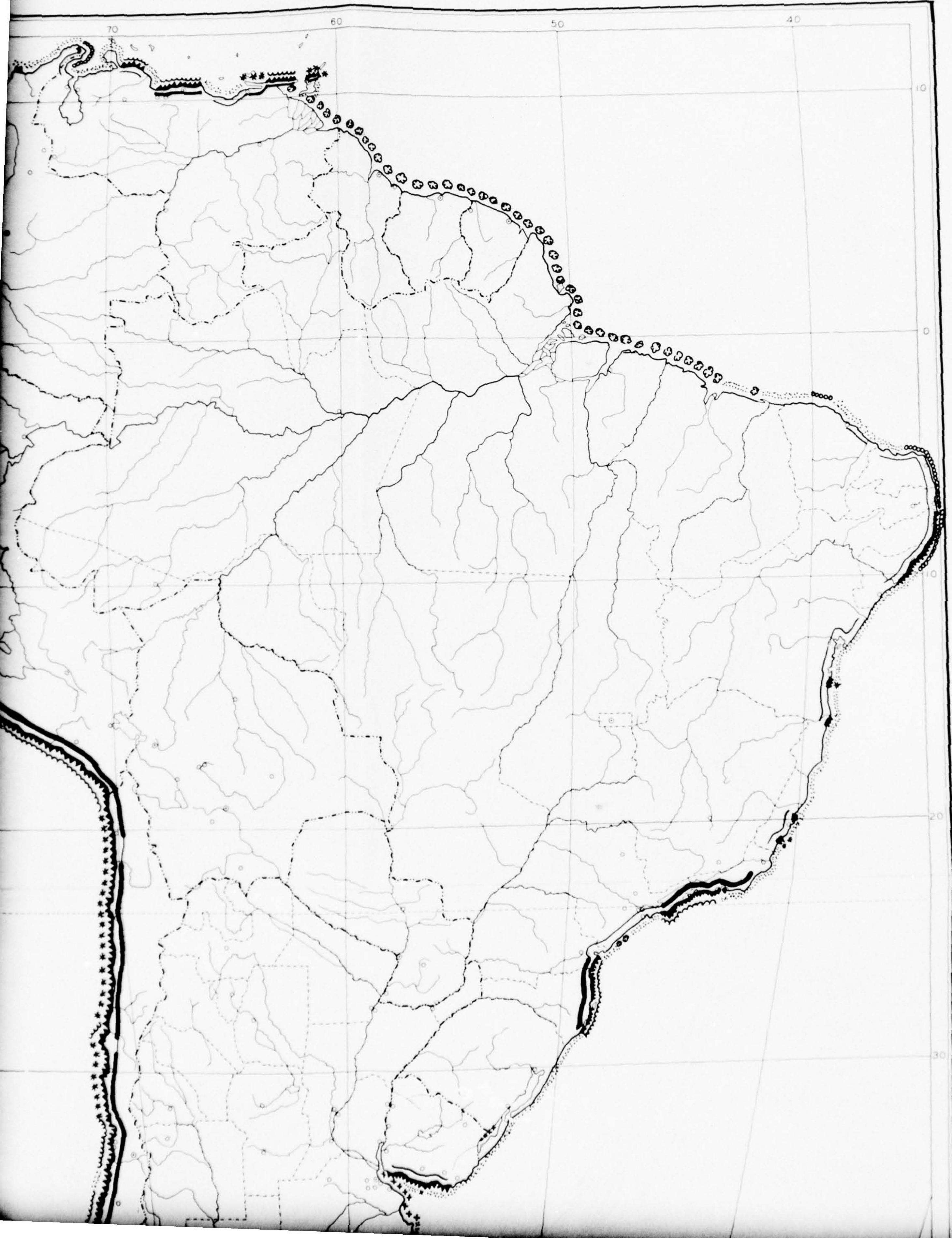
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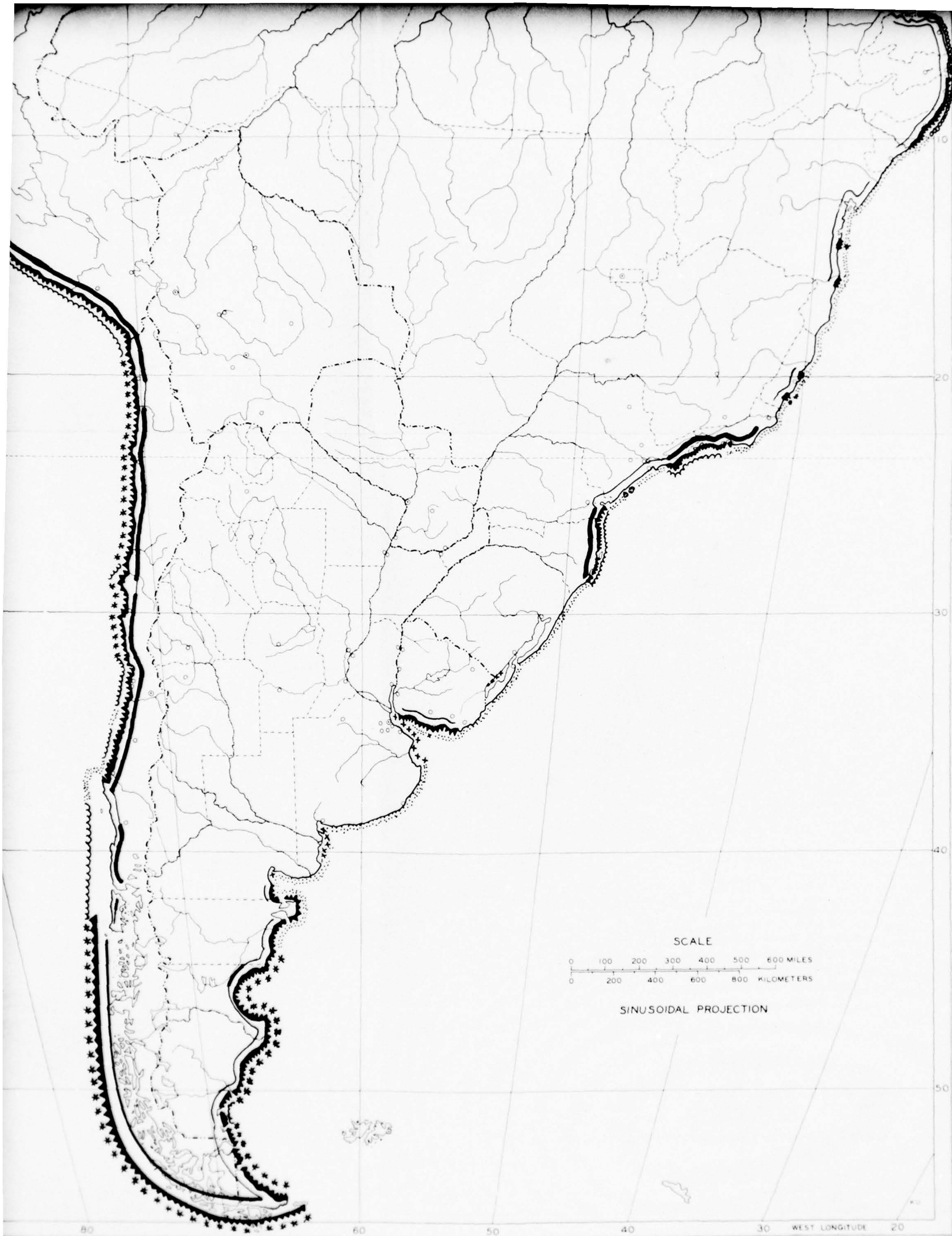
Fig. 3. Distribution of landform types of South America; 1 : 20,000,000.



orm types of South America; 1 : 20,000,000.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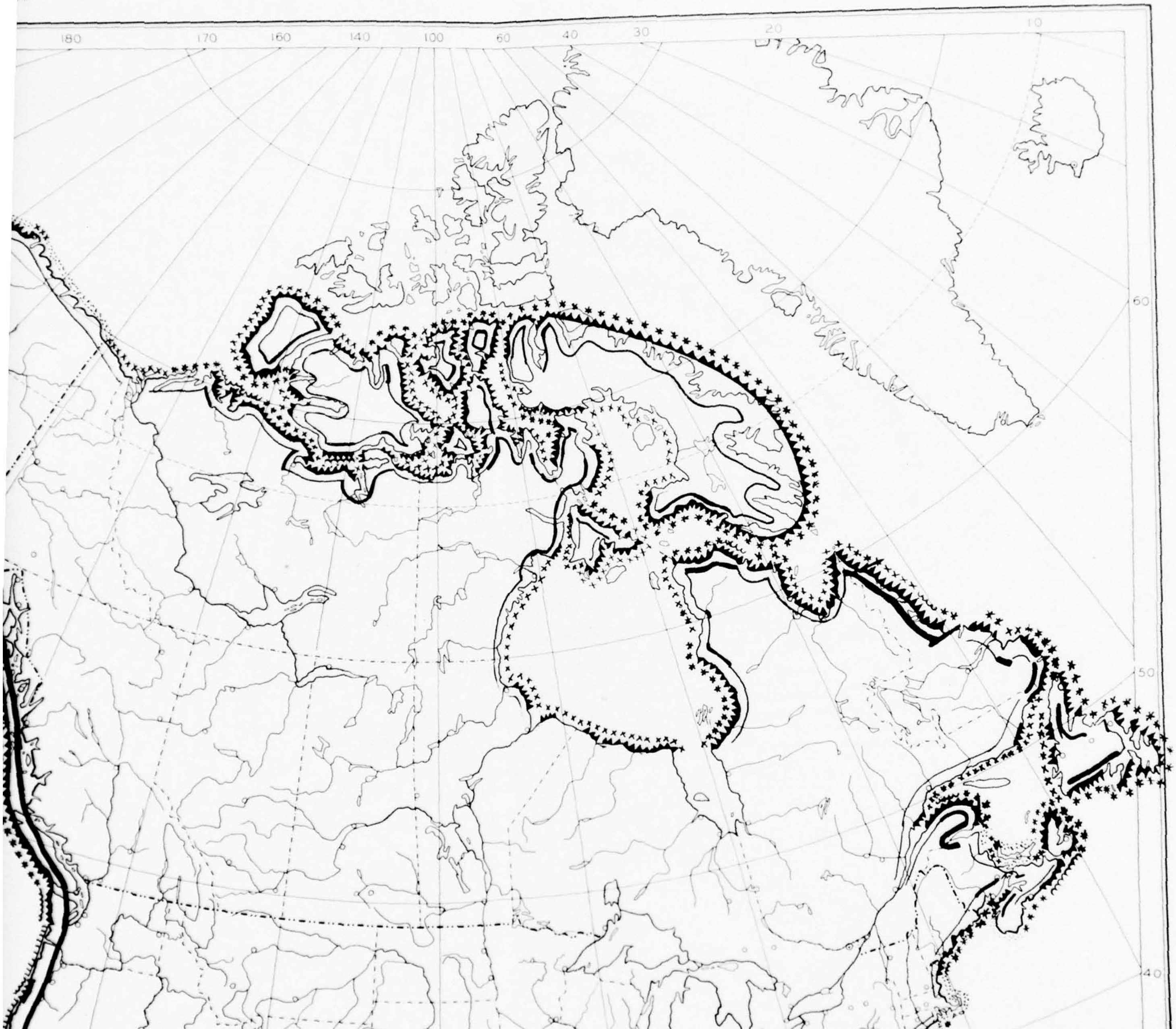


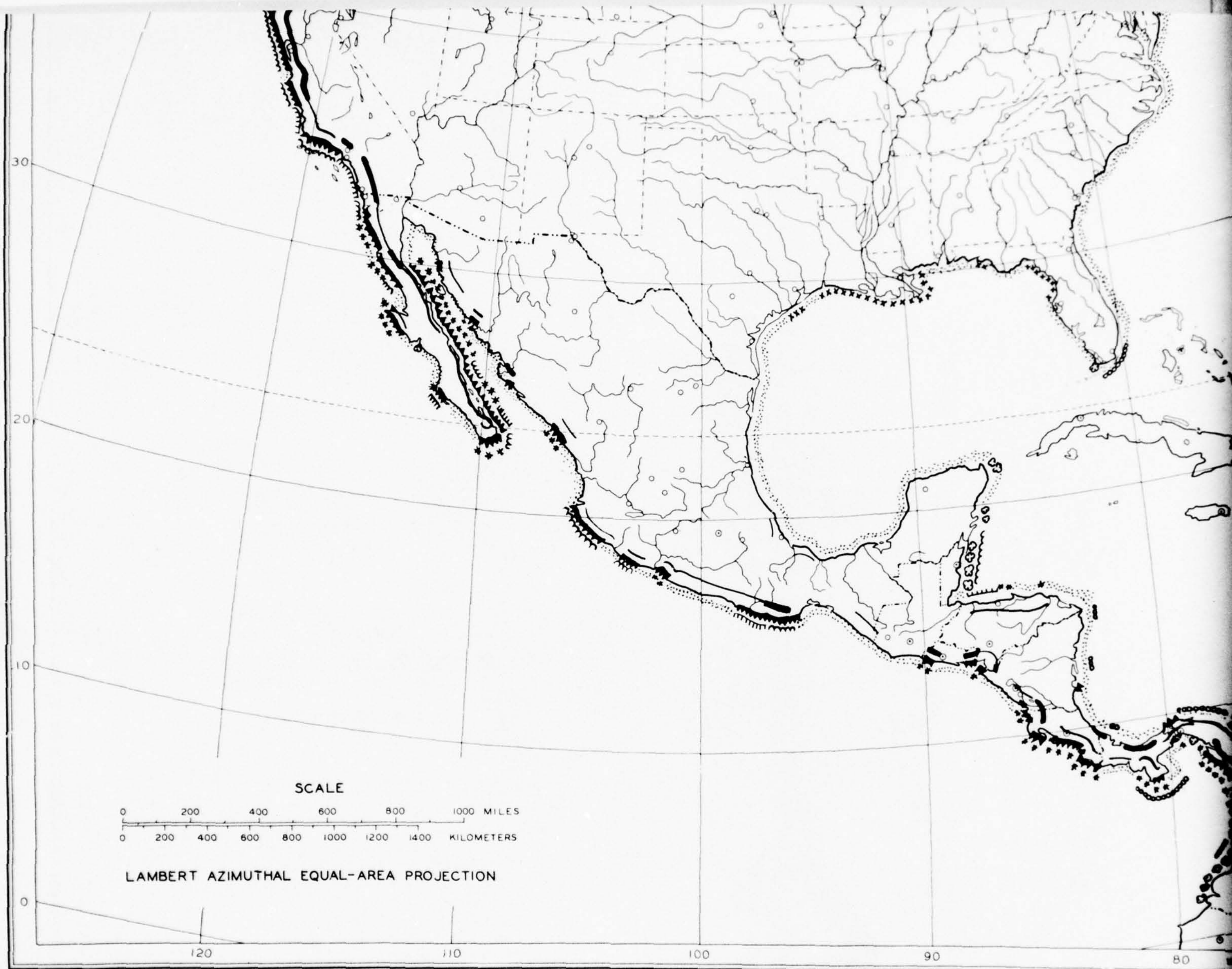
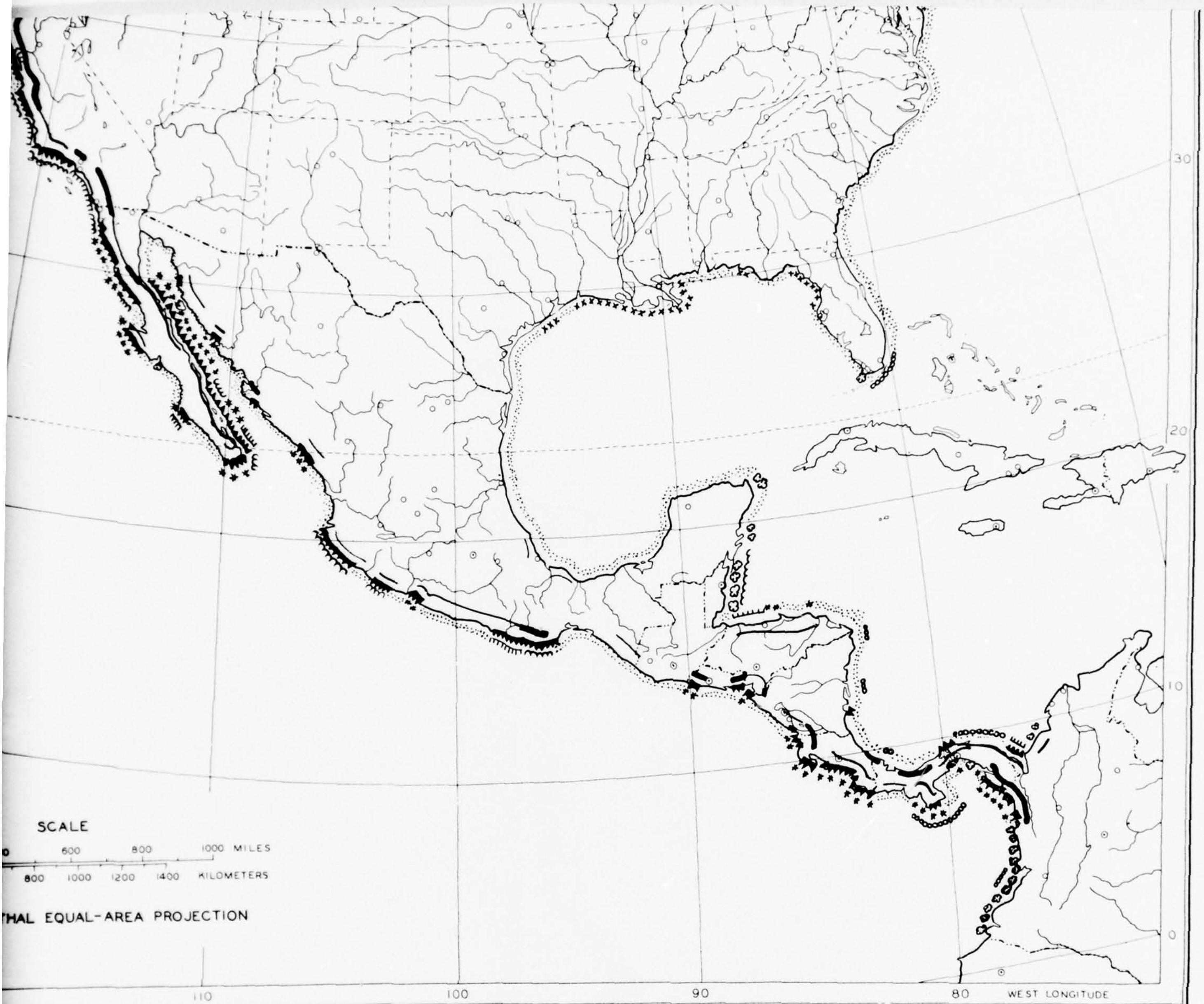


Fig. 2. Distribution of landform types of North America; 1 : 25,000,000.



es of North America; 1 : 25,000,000.

Table 4 — Occurrence of Relationships Among Components of the Landform Analysis

	Recent Volcanic	Older Resistant	Low Resistant	Recent Fluvial & Deltaic	Glacio-Fluvial	Total	Sand Beach Barrier Island	Sand Beach w/ Rock Hdl.	Pocket Beaches	Rocky	Mudflat – Marsh	Swamp – Mangrove	Coral	Total
High Relief Cliffed	2.0 / 1	32.24 / 30	3.4 / 3	0.0 / 0	0.0 / 0	37.27 / 34	1.2 / 1	0.0 / 0	4.12 / 6	29.13 / 24	2.0 / 2	0.0 / 0	0.0 / 0	37.27 / 34
High Relief	0.0 / 0	5.1 / 4	1.2 / 2	0.0 / 0	0.0 / 0	7.3 / 6	3.1 / 2	1.0 / 1	0.0 / 0	2.1 / 2	1.0 / 1	0.1 / 0	0.0 / 0	7.3 / 6
Low Relief Cliffed	0.0 / 0	13.4 / 10	2.8 / 4	0.0 / 0	0.3 / 1	15.15 / 15	1.4 / 2	0.0 / 0	2.3 / 3	4.6 / 4	8.0 / 6	0.0 / 0	0.1 / 0	15.15 / 15
Low Relief	1.0 / 0	12.4 / 10	4.4 / 4	0.0 / 0	2.0 / 1	19.7 / 16	5.5 / 5	0.0 / 0	1.0 / 0	2.0 / 2	11.0 / 8	0.0 / 0	0.0 / 0	19.7 / 16
Coastal Plain Cliffed	0.0 / 0	1.0 / 1	0.2 / 1	0.0 / 0	0.1 / 0	2.3 / 2	0.1 / 0	0.0 / 0	0.0 / 0	0.0 / 0	1.1 / 1	0.1 / 0	0.0 / 0	2.3 / 2
Coastal Plain	1.0 / 1	2.2 / 2	15.34 / 20	2.8 / 4	0.0 / 0	20.44 / 27	13.16 / 14	0.0 / 0	0.0 / 0	0.0 / 0	5.3 / 4	2.24 / 8	0.1 / 0	20.44 / 27
Total	4.0 / 2	66.34 / 57	26.54 / 34	2.8 / 4	2.4 / 2		23.30 / 25	2.1 / 2	8.15 / 10	37.20 / 32	29.4 / 22	2.26 / 9	0.3 / 1	
Sand Beach – Barrier Island	1.0 / 0	6.7 / 6	15.23 / 17	0.0 / 0	1.0 / 0	23.30 / 25								
Sand Beach with Rock Headlands	0.0 / 0	1.1 / 1	1.1 / 1	0.0 / 0	0.0 / 0	2.1 / 2								
Pocket Beaches	1.0 / 1	6.11 / 7	1.3 / 2	0.0 / 0	0.1 / 0	8.15 / 10								
Rocky	1.0 / 1	33.13 / 27	3.5 / 4	0.0 / 0	0.2 / 1	37.20 / 32								
Mudflats – Marsh	1.0 / 1	20.0 / 15	5.3 / 4	2.1 / 1	1.0 / 1	29.4 / 22								
Swamp – Mangrove	0.0 / 0	0.1 / 0	2.17 / 6	0.7 / 2	0.1 / 0	2.26 / 9								
Coral	0.0 / 0	0.1 / 0	0.2 / 1	0.0 / 0	0.0 / 0	0.3 / 1								
Total	4.0 / 3	66.34 / 57	26.54 / 34	2.8 / 4	3.4 / 3									

A. B % of total landform units
C

A = North America

B = South America

C = The Americas

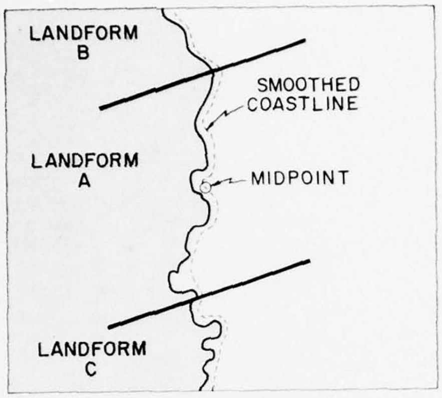


Fig. 4. Determination of length of a coastal unit by a smoothed coastline.

Comparison: Shoreline Characteristics of North America and South America

The percentage of shoreline type in each hemisphere of the Americas characterized by the various attributes of the landform classification is presented in table 3 while the relationships among these attributes is given in table 4. Several observations show the similarities and differences in continent orientation, shape, and position.

North and South America are similar in that each has an extensive western flank of generally resistant material and a southeastern flank of coastal plain. However, the two continents differ with respect to the shorelines with east-west orientation in the polar regions of the Northern Hemisphere and in tropical regions of the Southern Hemisphere.

In characteristics of coastal relief, North and South America are similar although South America has more coastal plain largely because of its tropical east-west axis. The continents differ significantly in lithologic characteristics: The North American east-west axis is dominated by older resistant material and the South American east-west axis is dominated by low-resistant materials. Sand beaches and barrier islands are equally common in both hemispheres and reflect the hemispheric similarity of east-facing coastlines. East-west axis shoreline characteristics of the two continents are dissimilar: The North American shoreline is dominated by mudflats and marshes, and the South American shoreline by swamps and mangroves.

Relationship: Shoreline Characteristics and Wave Climates

In order to establish relationships between shoreline characteristics and marine processes, the wave climates of the coastal zone of the Americas were classified. Data from Darling (1968), Galvin et al. (1969), Helle (1958), Russell (1969), U. S. Naval Oceanographic Office (1963), and the U. S. Naval Weather Service

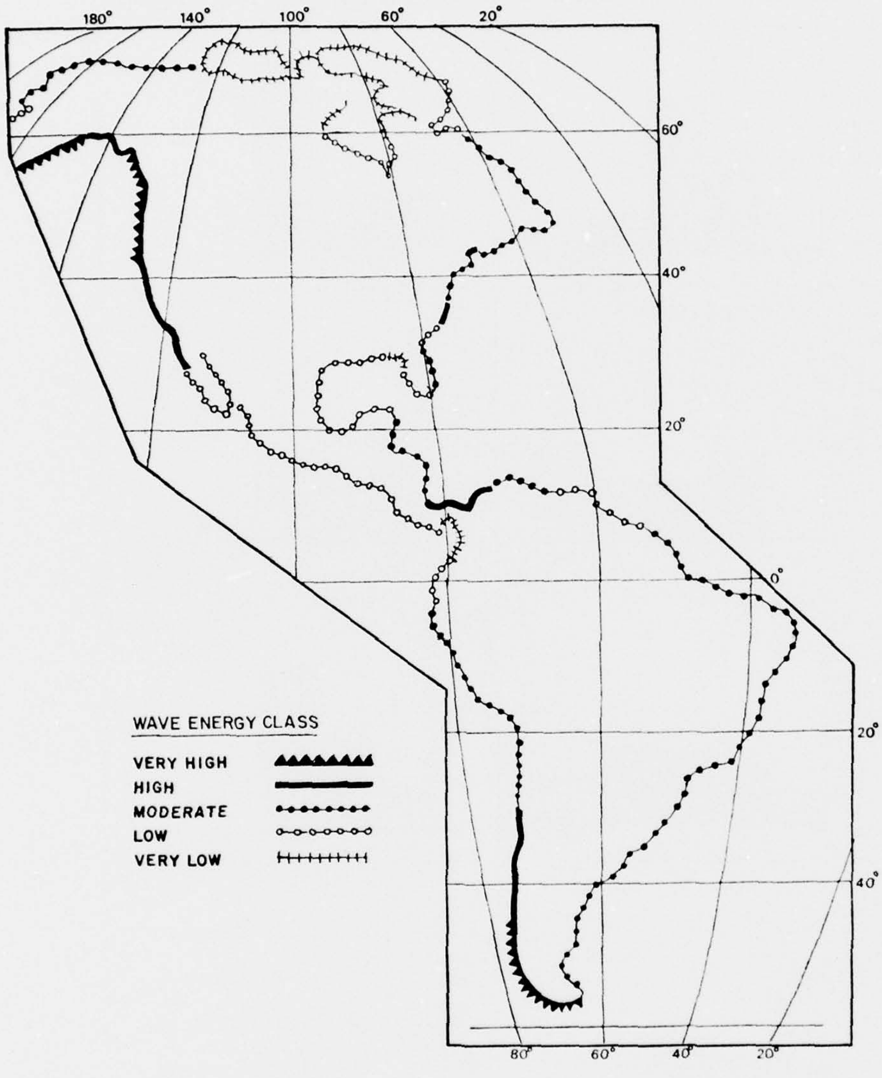


Fig. 5. Estimation of yearly mean wave energy.

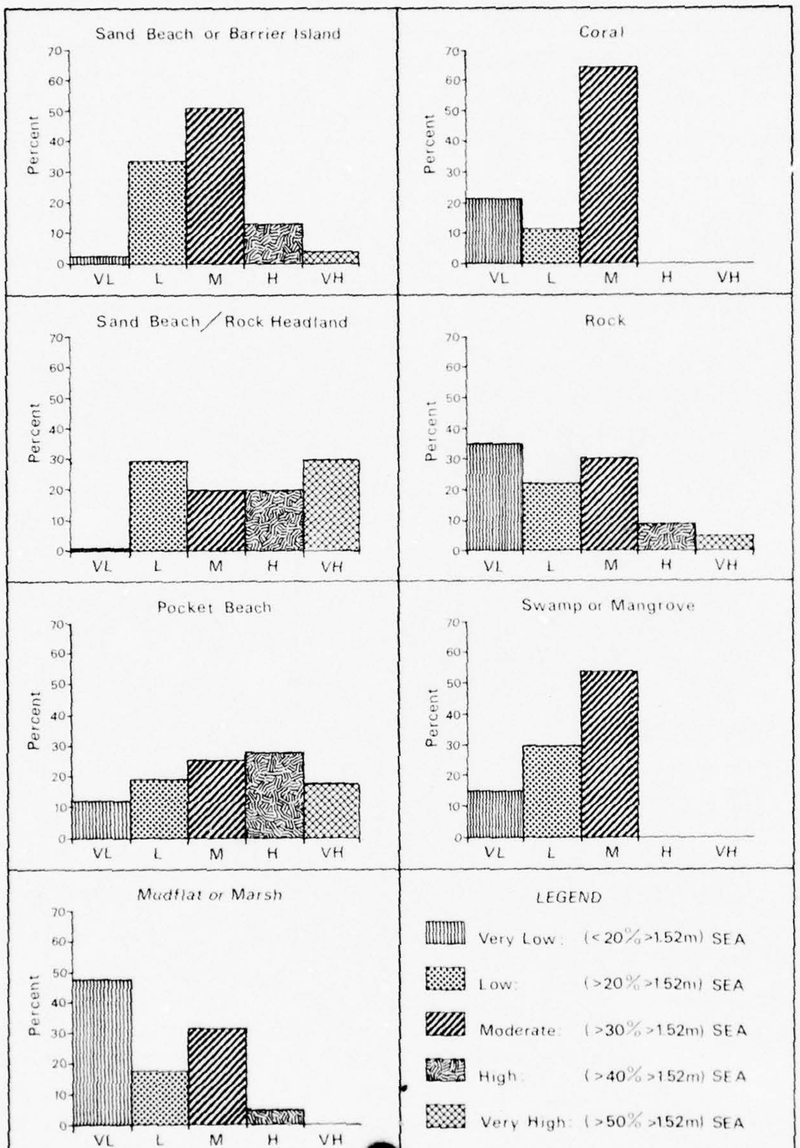


Fig. 6. Wave climate and shoreline type.

Command (SSMO Series) were assembled and stratified according to the wave energies focused on the coastline. Five wave classes are defined below (by yearly energy duration) and their distributions are shown in fig. 5.

1. Very High: Waves greater than 1.5 m (5 ft) more than 50 percent of the time.
2. High: Waves greater than 1.5 m (5 ft) 40–49 percent of the time.
3. Moderate: Waves greater than 1.5 m (5 ft) 30–39 percent of the time.
4. Low: Waves greater than 1.5 m (5 ft) 20–29 percent of the time.
5. Very low: Waves greater than 1.5 m (5 ft) less than 20 percent of the time.

The wave climate for each unit of shoreline type was recorded, and the percentage of shoreline type in each wave class calculated. The results show several noteworthy observations (fig. 6). For example, coral and mangrove shorelines are not found in regions of high or very high wave energy. Furthermore, over 50 percent of each of these shoreline types is dominated by moderate wave climates. Mudflats and marshes, frequently considered high-latitude analogs of coral and mangrove swamps, occur almost exclusively in areas of very low waves.

Sand beaches and barrier islands are found predominantly in areas of moderate wave energies. In areas of very high energy, the predominant shoreline types are pocket beaches and sand beaches with rock headlands. Rock shorelines occur more commonly in coastal areas of lower wave energies mainly because of the extensive areas of glaciated rocky coastline in central Canada.

While similar comparisons were made between relief and lithologic characteristics and wave climate classes, noteworthy relationships were few. Generally, coastal plains and cliffed coastal plains were found in regimes of low-to-moderate wave energies, and most of the coasts dominated by high and very high wave climates are of higher relief and are frequently cliffed. However, the reverse is not found to be true: High-relief and high-relief cliffed coasts are found in all wave climate classes.

Conclusion

In 1877, William Jevons pointed out:

Science can extend only so far as the power of accurate classification extends. If we cannot detect resemblances and assign their exact character and amount, we cannot have that generalized knowledge which constitutes science; we cannot infer from case to case (p. 730).

Of every class, so far as it is correctly formed, the principle of substitution is true, and whatever we know of one object in a class we know of the other objects . . . it is the . . . classifying and generalizing powers which enables the intellect of man to cope in some degree with the infinite number of natural phenomena (p. 674).

While the Classification of Coastal Landforms of the Americas is preliminary, the application of the classification in map form is, in effect, a call for further efforts clarifying natural discontinuities of coastal landforms.

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13. ABSTRACT

A new descriptive classification of coastal landforms based upon coastal lithology, topography, and shoreline type is presented with application to the coastal areas of the Americas on a scale of 1:20, 000,000. Hemispheric symmetry and departures from symmetry in the distribution of landform types are examined, and differences between North and South America are noted. The relationships between shoreline characteristics and coastal wave climates are analyzed, and the wave climate dependency for the more dynamic landform types is presented. Specifically, coral and mangrove shorelines were not found to occur in high wave-energy regimes, and more than 50% of recorded occurrences were in areas of moderate wave energies. Marsh and mudflat shorelines were almost exclusively restricted to areas of very low waves. Sand beaches and barrier islands were found pre-eminently in areas of moderate wave energies. In areas of the highest wave energies pocket beaches and sand beaches with rock headland dominate. (U)

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RECENT SECULAR VARIATIONS IN MID-ATLANTIC WINTER EXTRATROPICAL STORM CLIMATE

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Recent Secular Variations in Mid-Atlantic Winter Extratropical Storm Climate

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ABSTRACT

An increase in storm damage along the east coast of the United States coincides with secular variations of the general circulation documented by several recent investigations. To determine the coupling between large-scale circulation patterns and extratropical storms along the mid-Atlantic coast, a principal-component analysis is used to characterize patterns of 5-day mean surface pressure and, within objective categories of these patterns, conditional probabilities of storm occurrences are calculated. Based on this probabilistic coupling, secular variations in frequencies of surface pressure patterns are used to estimate secular variations in mid-Atlantic storm climate. The results suggest that a significant trend has occurred in large-scale circulation. Physical interpretation of this change suggests an increase in the frequency of high-latitude blocking. Associated recent secular changes in storm climate are 1) an offshore displacement of the mean storm track; 2) an increase in the number of storms moving offshore; and 3) a tendency toward two modes, rather than one, of storm tracks along the mid-Atlantic coast. Since such changes alter the frequency of extreme wave and surge conditions along the coast, the consequences are highly significant in terms of human impact.

1. Introduction

Based on economic criteria, the frequency of damaging storms along the east coast of the United States has risen from two or three per year in the 1920's and 1930's to over seven per year during the early 1960's (Mather *et al.*, 1964). As an index of secular change, an increase in damaging storms may be biased by increased coastal development and general shoreline recession. However, considerable independent evidence supports occurrence of secular changes in climate over the last century. Landsberg and Mitchell (1961) and Mitchell (1961) noted a worldwide warming trend culminating in the 1930's and a subsequent cooling. Lamb (1966) found significant changes in tropical rainfall regimes and documented recent long-term decreases in the strength of major zonal wind streams. Additionally, Lamb's (1966) and Kutzbach's (1970) results indicated significant changes in the large-scale circulation patterns. Commensurate changes in sea-surface temperature patterns have been reported by Namias (1969, 1972). If indeed recent changes in the general circulation have occurred, it is reasonable to suspect that the tracking of extratropical storms along the mid-Atlantic coast of the United States may also have changed. Evidence supporting this contention comes from a documentation by Bryson *et al.* (1970) of shifts in mean positions of major frontal systems in North America.

Kutzbach (1967, 1970) and Fritts *et al.* (1971) have demonstrated that multivariate statistical techniques can provide numerical characterizations of secular variations in the general circulation of the atmosphere. In this paper, coupling between large-scale circulation patterns, as specified by a principal-component analysis, and behavior of synoptic weather systems along the east coast of the United States is investigated. Conditional probabilities of storm tracks dependent on large-scale circulation patterns are used to establish secular changes in the winter extratropical storm climate along the mid-Atlantic coast.

2. Large-scale stratification of storms

Klein (1957) interpreted the distribution of storms off the east coast to be a single, broad storm track and no attempt was made to separate sources of variation other than by grouping storm tracks by month. Bowie and Weightman (1914), Miller (1946) and Andrews (1963) incorporated the type of location of cyclogenesis into their classifications of storm tracks. Although several investigations have indicated consistent relationships between large-scale circulation features and migratory lows (Sutcliffe and Fosdyke, 1950; Namias, 1968; Kuo, 1950, 1969), a systematic attempt to organize storm behavior on this basis is

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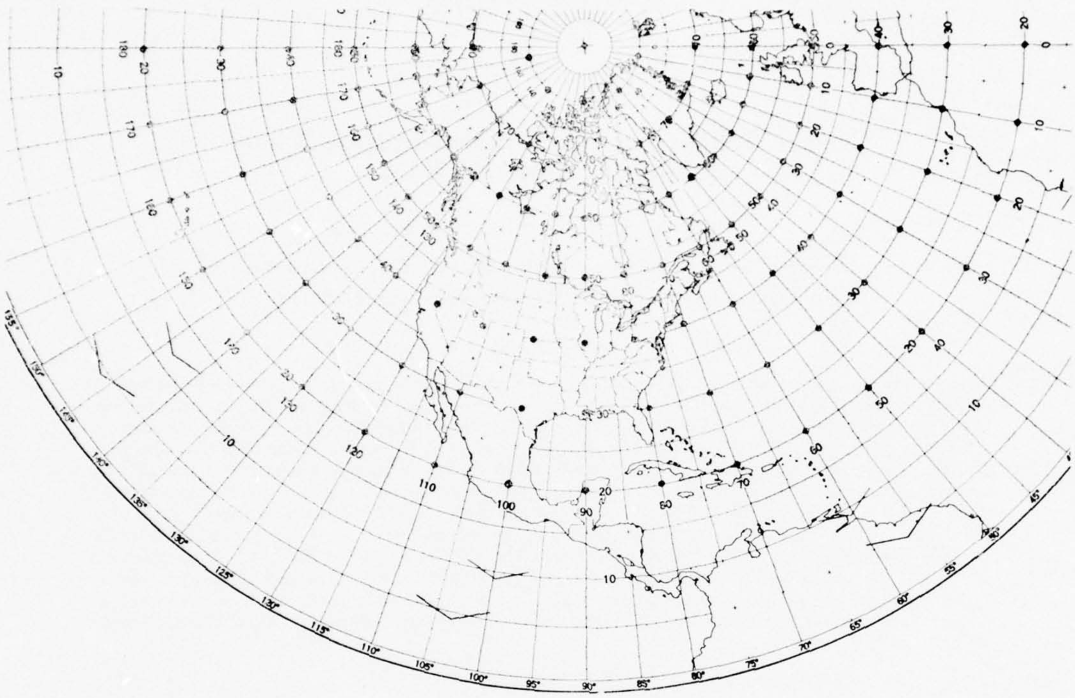


FIG. 1. Grid points for surface pressure data which are input to principal-component analysis. Spacing of points is 10° latitude by 10° longitude between 20°N and 60°N. North of 60° the spacing is adjusted to give approximately equal distances between points.

lacking. Since storms represent perturbations in time-averaged or large-scale flows and are affected by factors other than the large-scale features, the nature of the link between the two atmospheric scales of motion is probabilistic rather than deterministic. Consequently, large-scale patterns are used in this study to stratify storm behavior, not to forecast exact movement or development.

In terms of least-square error, principal-component analysis provides an optimal means of objectively specifying patterns in large fields of data (Lorenz, 1956; Gilman, 1957; Kutzbach, 1967). Basically, the analysis transforms a set of intercorrelated variates into a new coordinate system with inherent statistical properties. The axes in the new coordinate system are linear combinations of the original variates and are mutually orthogonal.

A 111-point grid was chosen to cover the region from 0° to 180°W longitude and 20° to 90°N latitude (Fig. 1). Daily pressures were available at these points on magnetic tapes from the National Weather Service in Suitland, Md. These data were obtained for December through March of the years 1899–1938 and 1947–1970. Since December 1899 and 1946 are not available, the winters of 1899 and 1947 are not complete. This leaves 62 years of complete data and two years with only three months of data. These data were averaged into 5-day increments beginning with 1–5 December and running through 24–29 March or 25–30 March for leap years.

An SSCP (sum of squares and cross product) matrix for the 111-point grid was calculated from 5-day mean surface pressures:

$$ {}_m\mathbf{A}_m = {}_m\mathbf{G}_n\mathbf{G}'_m, \quad n=1{,}564, \quad m=111, \qquad (1)$$

where ${}_m\mathbf{A}_m$ is the SSCP matrix of the 111 grid points of 5-day mean surface pressure, ${}_m\mathbf{G}_n$ the observation matrix, and ${}_n\mathbf{G}'_m$ the transpose of the observation matrix.

TABLE 1. The percentage of the total variance and cumulative percentage of total variance of 5-day mean surface pressures associated with eigenvectors 1–8. The values in column two are equal to the corresponding eigenvalue divided by the sum of all 111 eigenvalues.

Eigenvector	Percentage of variance explained	Cumulative percentage of variance explained
1	87.25	87.25
2	3.39	90.64
3	1.98	92.61
4	1.39	94.00
5	1.10	95.11
6	0.98	96.09
7	0.73	96.81
8	0.68	97.49

The eigenvalues and eigenvectors of the covariance matrix were calculated in the usual manner,

$$ {}_m\mathbf{A}_m\mathbf{E}_m = {}_m\mathbf{E}_m\mathbf{L}_m, \tag{2} $$

where ${}_m\mathbf{E}_m$ is the complete eigenvector matrix corresponding to the eigenvalues L_i $(i=1, m)$. The variance explained by the first eight eigenvectors is given in Table 1, and the eigenvectors corresponding to eigenvalues 2 through 8 are mapped in Figs. 2 and 3. Eigenvector 1 is not mapped because it has approximately the same weighting on each grid point and cannot be contoured with the same contour interval as the others. In that the SSCP matrix was used, rather than the covariance matrix, the magnitude of the first eigenvalue is large (Table 1). This does not lower the significance of the higher order eigenvectors.

Objective specification of large-scale patterns of 5-day mean surface pressure was obtained by forming the inner product between the observation matrix and the first eight eigenvectors

$$ {}_k\mathbf{W}_n = {}_k\mathbf{E}_m\mathbf{G}'_n, \tag{3} $$

where ${}_k\mathbf{E}_m$ is the transpose of the matrix containing the first eight columns (the first eight eigenvectors) of the complete eigenvector matrix and ${}_k\mathbf{W}_n$ is a matrix containing the weightings of each 5-day mean surface pressure on the first eight eigenvectors. On the basis of the position and magnitude of pressure anomalies, three eigenvectors, E_2, E_3 and E_4, were chosen to stratify the 5-day time increments. Since no pronounced modes or other divisions were evident in the distributions of these eigenvector weights, the method of dissection was used to obtain classes of large-scale patterns.

Each eigenvector was partitioned into three categories of weights:

$$ \left.\begin{array}{ll} 1) & W_i < -30 \\ 2) & -30 \leq W_i \leq 30 \\ 3) & W_i > 30 \end{array}\right\}, $$

where W_i represents the weighting of a 5-day mean pressure on eigenvector i $(i=2, 3, 4)$ calculated from Eq. (3). The choice of rather large ranges for these categories was prompted by two factors. First, the reliability of the results is higher for a small number of categories than for a large number of categories. Second, this study is not intended to provide an exact, time-dependent probability of storm behavior. Since probability is a property of long-term frequencies, such a solution would be meaningless. Rather, this study attempts only to determine the existence or non-existence of secular trends in storm behavior.

3. Specification of conditional probabilities for extratropical storms

Storm tracks were mapped for a sample of 504 extratropical storms which passed through some part of the grid area shown in Fig. 4 during the months of December through March in the years 1899–1938 and 1947–1965. The source of this information is the *Daily Synoptic Series of Historical Weather Maps: Northern Hemisphere, Sea Level*, as prepared by the U. S. Weather Bureau in cooperation with the Army, Navy and Air Force. Even though some error is inherent in interpolations of storm track between daily storm positions, mapping techniques were consistent. Consequently no bias through time is expected.

In order to analyze the organization of storm movement, storm tracks were grouped according to the following spatial criteria:

1) Storms which originated outside of the area shown in Fig. 4 were classed according to their point of entry into the area.

2) Storms which originated within the area shown in Fig. 4 were classed according to the point at which the storm was first manifest in the surface pressure field.

Baselines of the grid in Fig. 4 are 35°N and 75° 30′W. The dimensions of the grid cells are 2° latitude by 2.5° longitude in the area adjacent to shore. Reasons for the nature of the grid used in this study lie in the variability of wave and surge generation from storms characterized in this manner (Resio and Hayden, 1973). Seventeen storm types are defined: seven enter into the grid area through line segments 1 through 7; and ten originate within grid blocks a through j. For consistency, storm tracks were assigned to the 5-day period in which the storm center was closest to the center of grid block d. Storm types a, b and c; d and g; e and h; and f and i were combined to accumulate a sufficient sample for the purpose of defining distributions of cyclogenesis and storm movement within storm categories. Individual storm tracks were mapped onto the same map for all storms occurring within each storm type, regardless of its large-scale classification. The results indicate a pronounced regularity for storms thus stratified.

From a sample of 1071 5-day periods, the ratio of the number of storms to the number of 5-day periods sampled was calculated for categories based on eigenvectors 2, 3 and 4 (Table 2). This ratio is equal to the probability of a storm occurring during a 5-day period and for convenience is termed storm frequency.

TABLE 2. Matrix expressing storm frequency (average number of storms per 5-day period) within categories of large-scale circulation patterns based on eigenvectors 2, 3 and 4 of 5-day mean surface pressure.

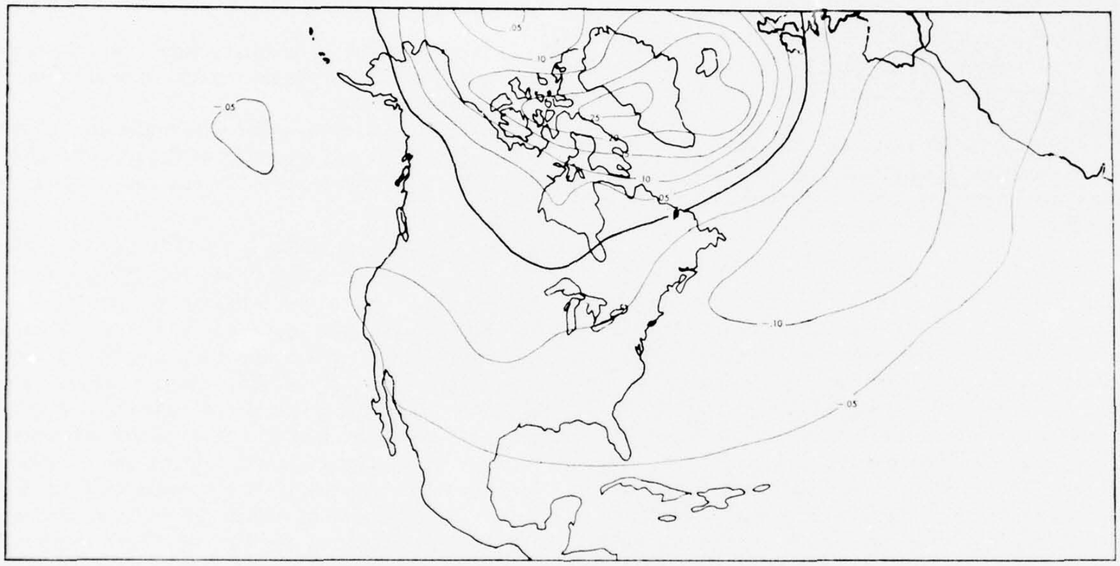
Eigenvector	$W_i < -30$	$-30 \leq W_i \leq 30$	$W_i > 30$
2	0.3726	0.4941	0.5469
3	0.5000	0.4599	0.4857
4	0.4583	0.4506	0.5957

Within eigenvector categories, the conditional probability for each of the twelve storm types, given that a storm does occur, was calculated. Given that the effects of E_2, E_3 and E_4 are independent, the probability of storm track i occurring during a 5-day period can be expressed as

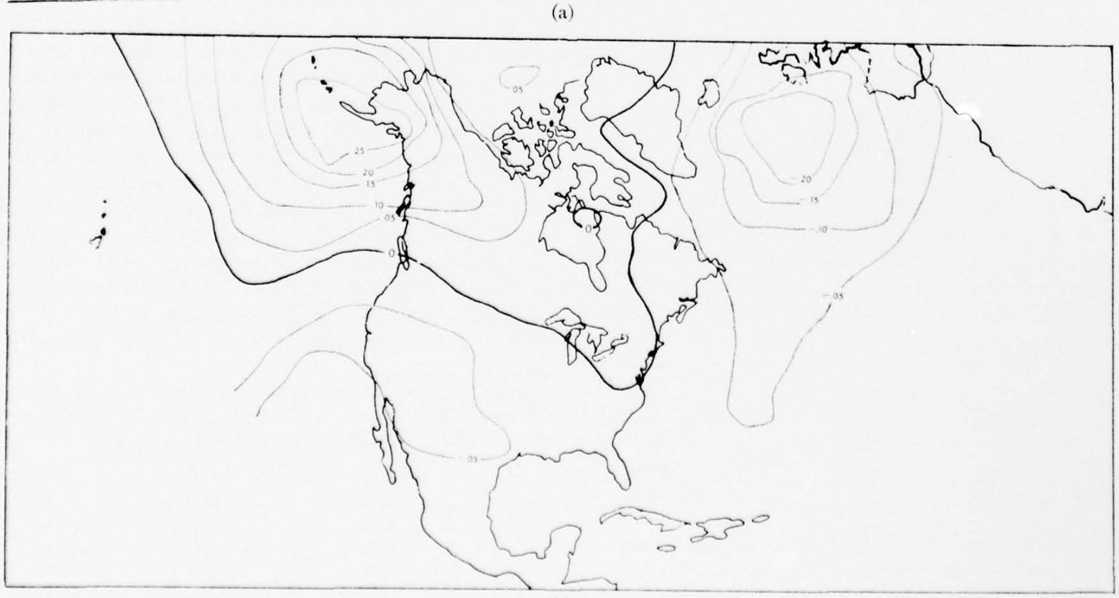
$$P(T_i)=\left[\sum_{j=1}^{3} P'(T_i|E_2=j)P(S|E_2=j)P(E_2=j)\right]\phi_1\phi_2, \tag{4}$$

where $P'(T_i|E_2=j)$ is the conditional probability of storm type i given that a storm does occur and that the circulation pattern based on eigenvector 2 is within category j; $P(S|E_2=j)$ is the conditional probability of having a storm, given that the circulation pattern based on eigenvector 2 is within category j; $P(E_2=j)$ is the probability of occurrence of circulation patterns within category j; and ϕ_1 and ϕ_2 are defined as

$$\phi_1=\frac{\sum_{k=1}^{3} P'(T_i|E_3=k)P(S|E_3=k)P(E_3=k)}{\bar{P}}, \tag{5}$$

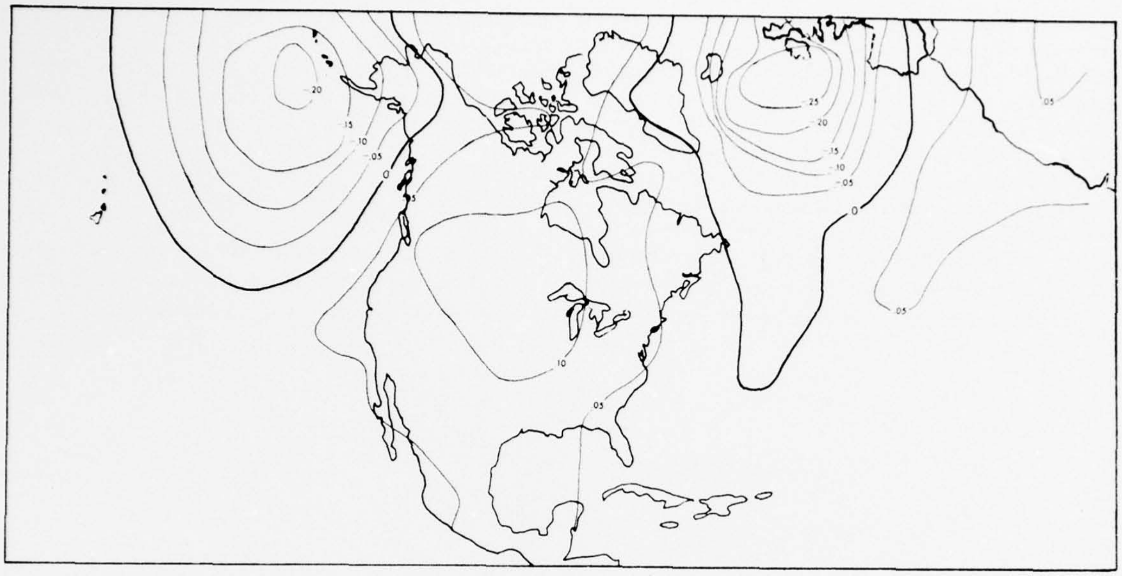


(a)

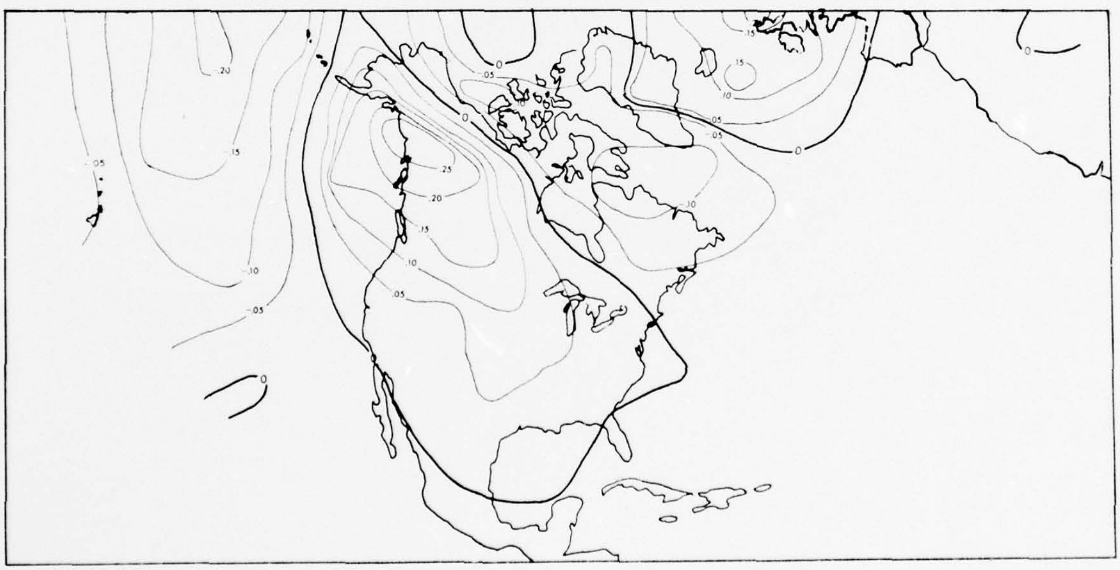


(b)

FIG. 2. Second eigenvector (a) of 5-day mean surface pressure (E_2); third eigenvector (b) of 5-day mean surface pressure (E_3); fourth eigenvector (c) of 5-day mean surface pressure (E_4); and fifth eigenvector (d) of 5-day mean surface pressure (E_5).



(c)



(d)

FIG. 2. *Continued.*

$$\phi_2 = \frac{\sum_{l=1}^{3} P'(T_i|E_4=l)P(S|E_4=l)P(E_4=l)}{\bar{P}}, \tag{6}$$

where $\bar{P}$ is the mean probability of storm type i for the entire sample and the other terms are analogous to terms in Eq. (4).

The validity of the assumption of independence for large-scale effects on storm frequency was tested by calculating storm frequency within each large-scale category and was compared with storm frequencies estimated from the relation

$$P(S|E_2=j, E_3=K, E_4=l) = P(S|E_2=j) \times \frac{P(S|E_3=k)}{\bar{P}} \frac{P(S|E_4=l)}{\bar{P}}. \tag{7}$$

The correlation between this estimate of storm fre-

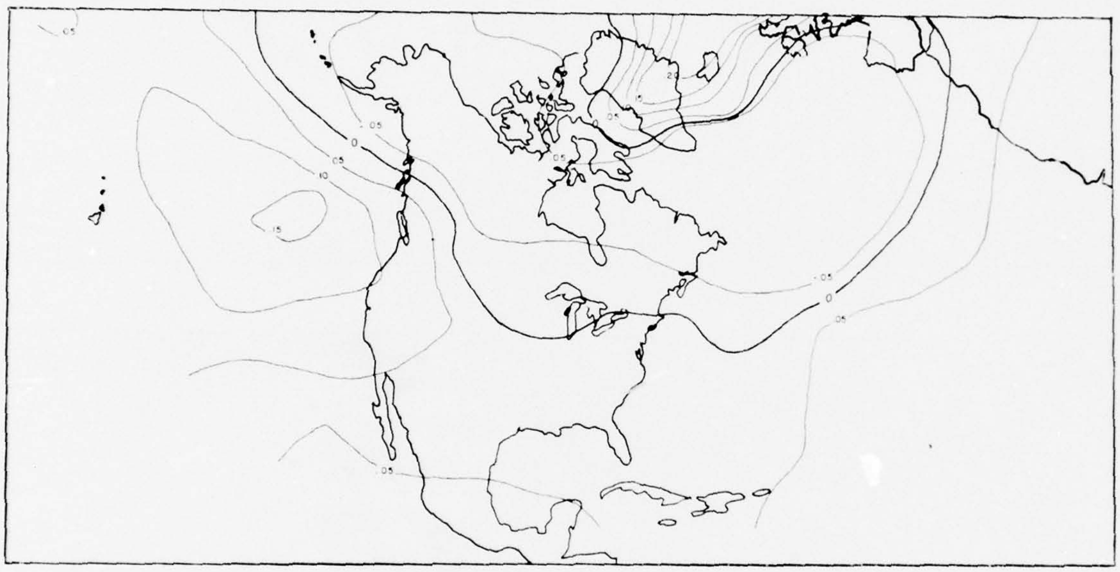
quency and the actual number of storms within large-scale categories was 0.999. There are insufficient data to investigate storm types within large-scale categories.

Before Eq. (4) was applied to the estimation of secular variations in storm-track frequency, the correlation between time and storm frequency independent of the large-scale classification was investigated. Contingency tables were constructed for storm frequency within decades for two large-scale categories, and χ^2 values were calculated for each in the manner recommended by Cochran (1952). The χ^2 values from these tables, 1.54 and 1.93, were not significant even at the 0.5 level, indicating that the large-scale categorization successfully stratifies most of the variation in storm frequency.

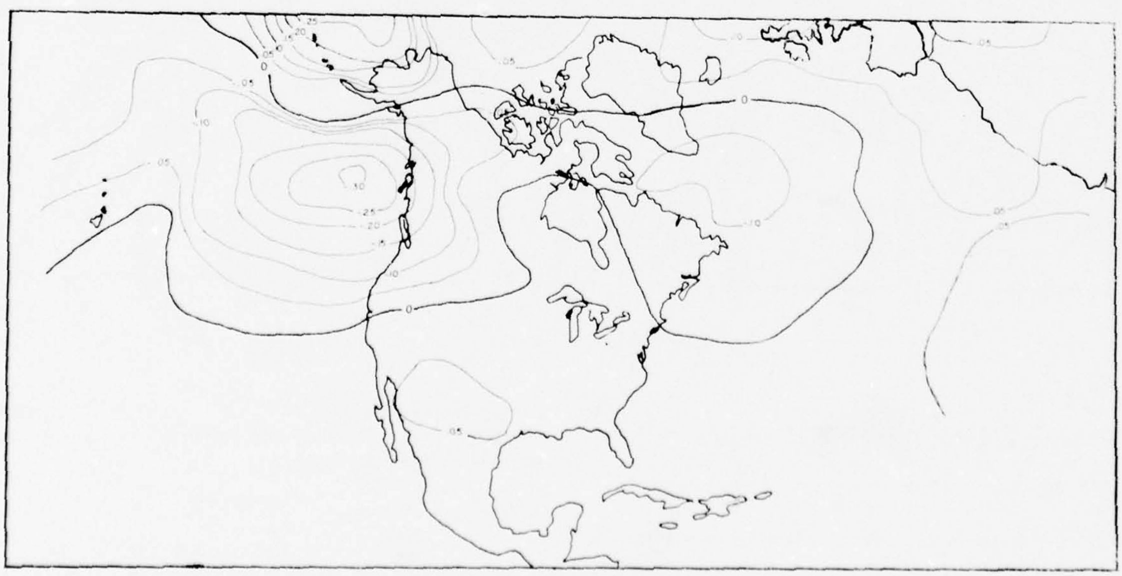
4. Results

a. Variation in large-scale circulation patterns, 1899–1970

Mean weightings on the first eight eigenvectors of 5-day mean pressure were calculated for each winter

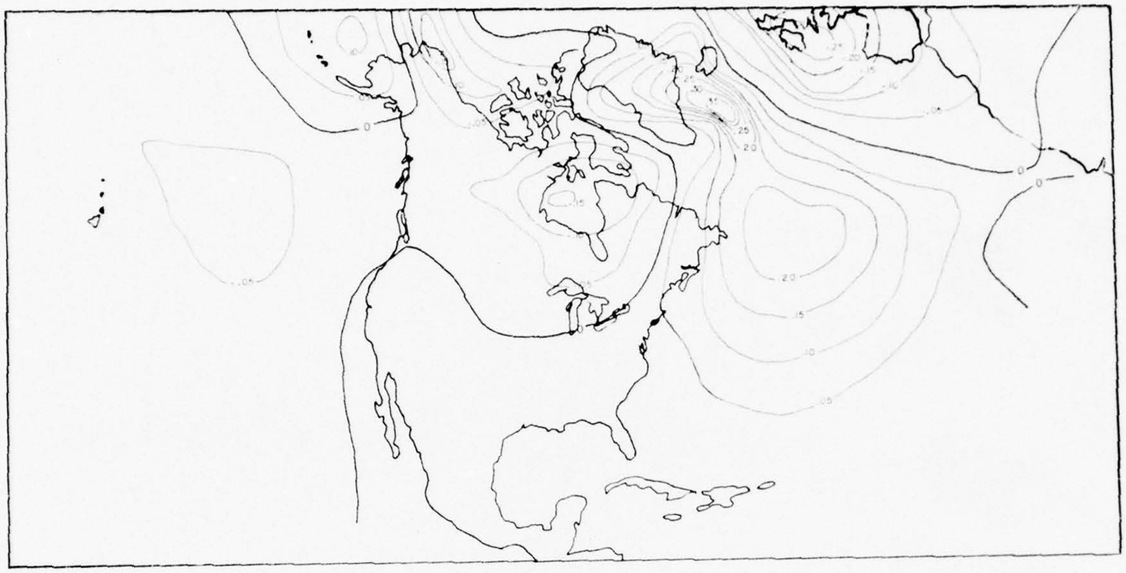


(a)



(b)

FIG. 3. As in Fig. 2 except for sixth, seventh and eighth eigenvectors of 5-day mean surface pressure.



(c)

FIG. 3. *Continued.*

(Fig. 5). Only the pattern represented in eigenvector 2 undergoes a pronounced secular trend in the period from 1899–1970. To test the significance of this trend, the number of 5-day periods within large-scale categories based on eigenvector 2 was obtained for each decade of the 1900's and tested as a contingency table. The χ^2 value for this contingency table is 86.74 and with 13 degrees of freedom is significant above the 0.001 level. Thus, it appears that the trend in large-scale circulation patterns associated with the weights on eigenvector 2 is beyond what might normally be expected from random deviations.

The time series of average weights on eigenvector 2 suggests a broad minima of weights or maxima of negative weights extending into the 1920's followed by a trend toward frequencies of circulation patterns more closely resembling the early 1900's and perhaps earlier periods.

Supporting evidence for the existence of such a climatic change in the 1900's comes from several recent investigations. There has been a pronounced change in sea-surface temperature patterns in the 1960's associated with a reversal of the climatic warming trend of the early 1900's (Namias, 1969); and since 1964, the distribution of sea-surface temperatures in the North Atlantic has come to resemble the pattern revealed by the surveys between 1780 and 1850 (Lamb, 1966). The strength of the main zonal wind streams in most parts of the world has been decreasing since a maximum dated approximately in 1925 (Lamb, 1966). Associated with this reduction in zonal wind velocities has been an increase in the frequency of blocking highs at high latitudes during the 1960's (Lamb, 1966). Rainfall regimes in tropical Africa in the 1960's appear to resemble more closely nineteenth century normals than normals of the early 1900's (Lamb, 1966). Temperature patterns in the United States during the 1960's appear to have returned to patterns similar to the early 1800's (Wahl and Lawson, 1970). On a worldwide basis, trends in zonally averaged temperatures reflect the same tendency to return to climatic regimes of the 1800's (Mitchell, 1961).

The indication of an increase in the frequency of blocking highs at high latitudes is especially relevant to the physical interpretation of eigenvector 2. It is

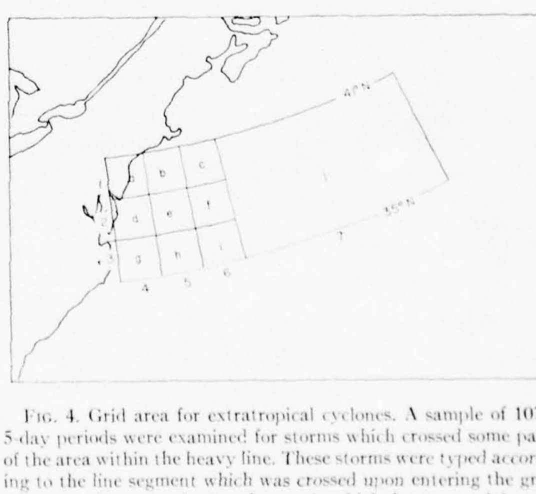


FIG. 4. Grid area for extratropical cyclones. A sample of 1071 5-day periods were examined for storms which crossed some part of the area within the heavy line. These storms were typed according to the line segment which was crossed upon entering the grid (designated by a number) or the area in which the storm originated within the grid (designated by a letter).

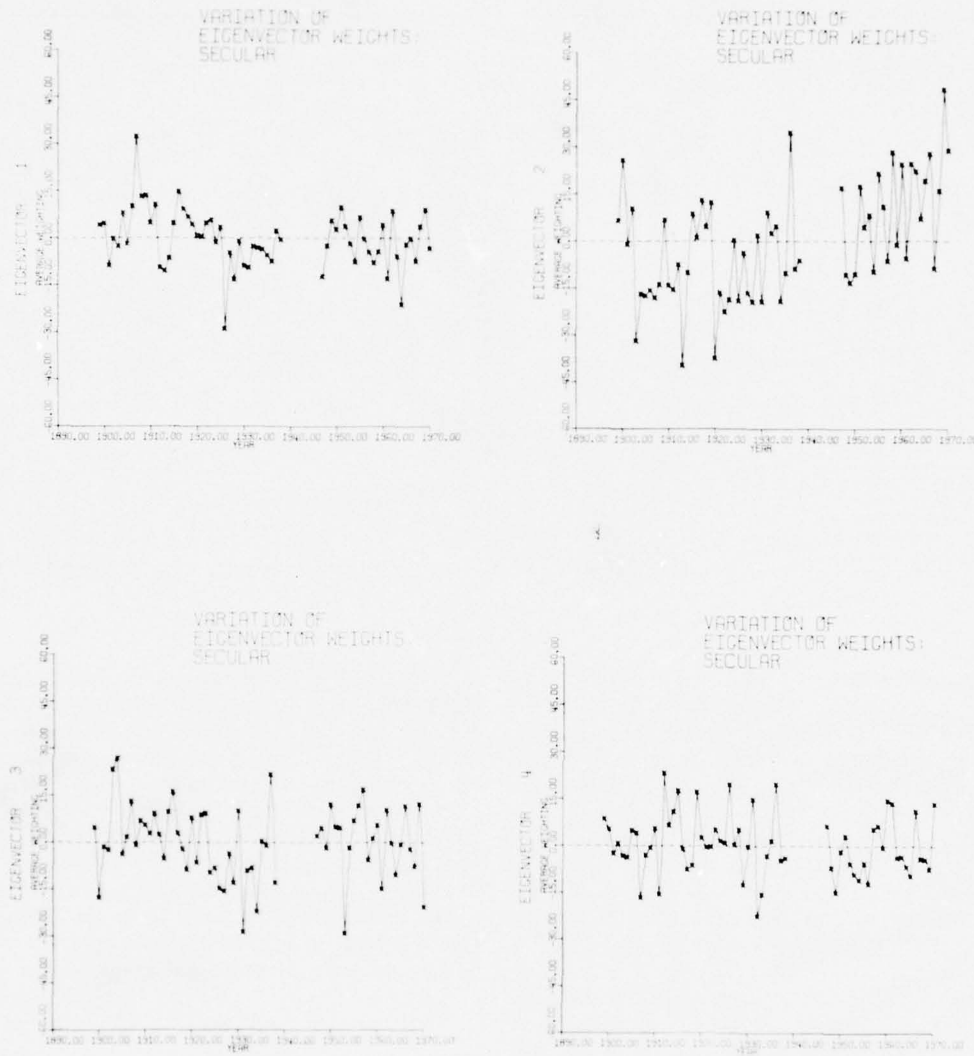


FIG. 5. Time variation of the mean annual weighting on the first eight eigenvectors, 1899–1938 and 1947–1970.

plausible that the mean anomaly created by an increase in high-latitude blocking might resemble this pattern with a band of low pressure extending across the Atlantic Ocean and higher pressure extending to the north. The consistency between some indices of blocking and weightings of eigenvector 2 are shown in Fig. 6.

b. Variation in extratropical storm climate 1899–1970

As shown in Fig. 5, large-scale circulation patterns associated with the eigenvectors used to stratify storm behavior in this study (E_2, E_3, E_4) have varied through time. Even though average winter weightings on eigenvector 2 are the only data which contain a pronounced secular trend, the data for eigenvectors 3 and 4 contain temporal anomalies on the order of decades. Consequently, an attempt to reconstruct storm climates for past periods of time requires the use of all three eigenvectors.

From Eq. (4), storm-type frequencies were calculated for each decade of the 1900's (Table 3). On the basis of mean annual weightings on eigenvector 2, the 1920's and 1960's were shown to be those most dissimilar during the period 1899–1970. Fig. 7 illustrates the differences between these decades in terms of storm behavior. Overall, there is a 9.6% increase in storm activity off the mid-Atlantic coast. However, changes in the spatial distribution of storms make the increase much higher for some areas. The distribution of storms crossing into the grid area in the 1960's is markedly more bimodal than in the 1920's, with maxima in storm types 2 and 5. Additionally, the

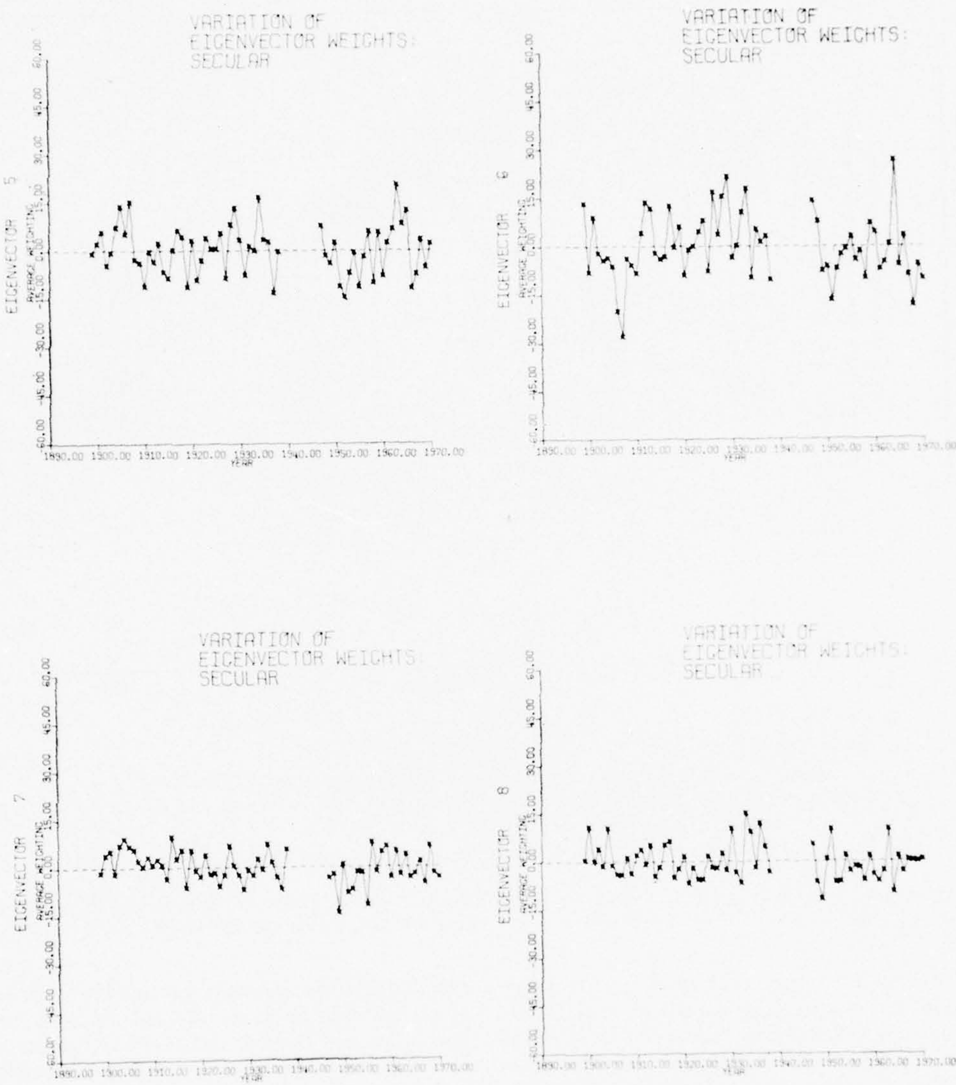
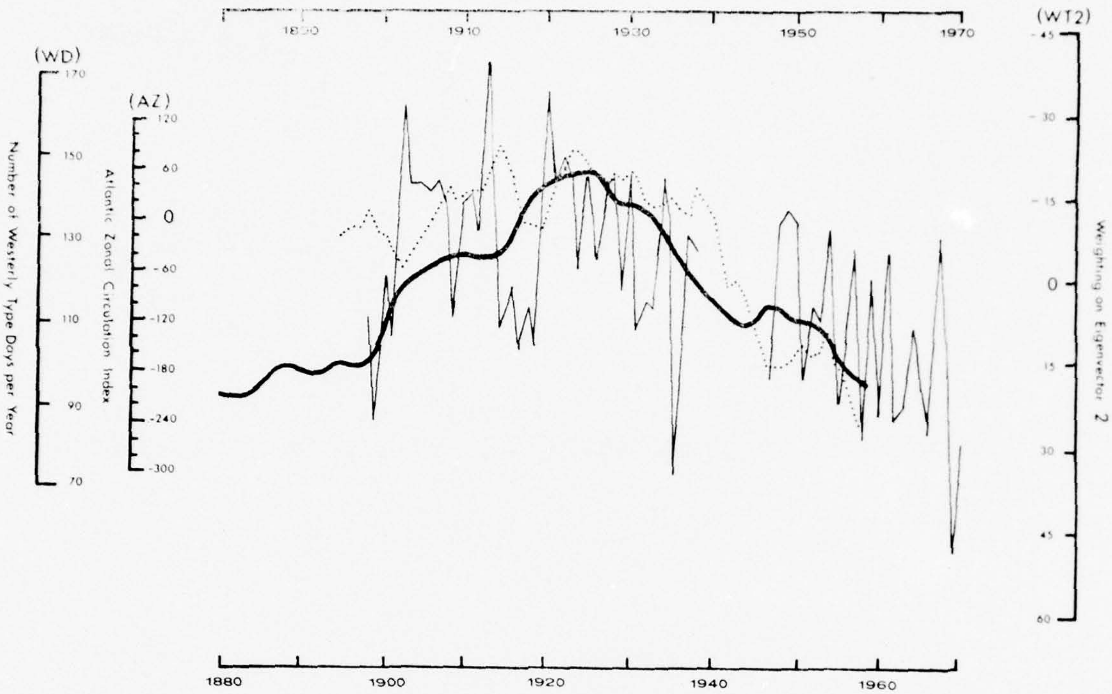


Fig. 5. *Continued.*

mean storm track shows a displacement offshore evidenced by a decrease in storm type 4 and increases in storm types farther offshore (except storm type j).

The increase in the bimodality of the storm population is difficult to relate to a specific property of the large-scale circulation, but the offshore displacement of storms can be linked directly to the increased frequency of high-latitude blocking. During periods of high-latitude blocking, large anticyclones dominate the Greenland-Davis Strait region and impede the normal course of extratropical cyclones, forcing the movement of lows to deviate toward the east; hence the offshore displacement of the track.

Studies by Mather *et al.* (1964) and Bosserman and Dolan (1968) offer some aspects of comparison for these results. Mather *et al.* document a change in the number of damaging storms from 2–3 per year in the 1920's to over 7 per year in the 1960's. This trend is obviously much larger than expected due to the overall increased storm frequency estimated by Eq. (4). Nonclimatic factors such as increased coastal development, general shoreline recession, or bias in storm-damage reports might explain the discrepancy between the magnitude of the increase in damaging storms compared to the lower overall increase in storm frequency.



——— WT2	=	Mean annual weighting on Eigenvector 2.
.... AZ	=	Atlantic zonal circulation index: annual average values of the Azores-Iceland pressure difference expressed in % of its overall average 1894-1952 (Lamb, 1966).
━━━ WD	=	Frequency of westerly type days in the British Isles (Lamb, 1965).

FIG. 6. Comparison of mean annual weighting on eigenvector 2 of 5-day mean surface pressure with the average annual Atlantic zonal circulation index (Lamb, 1966) and the annual frequency of westerly type days in the British Isles (Lamb, 1965).

Support for both the number of extratropical storms per year and the magnitude of the secular variation in storm frequency estimated in this study is found in Bosserman and Dolan (1968). During the period from 1943–67, they recorded an average of 17.2 storms per winter along the Atlantic Coast. Of these storms 22.3% were migratory anticyclones and 14.0% were storms outside of the grid area considered in this study. This leaves 10.9 storms per year which are comparable. Using the mean storm frequency of the data for 1947–70 from this study (0.4645), the total number of storms per winter is estimated to be 11.1. From the 1940's to the 1960's, Bosserman and Dolan's data show an increase of 2.2 storms per winter from 16.4 to 18.6. This is equivalent to an increase in storm frequency of 13.4% which compares reasonably well with the 8.9% increase in storm frequency from the 1940's to the 1960's estimated in this study.

A source of evidence supporting both the increase in storm frequency and offshore displacement of storms comes from Wahl and Lawson (1970). Their map of the temperature anomaly for the 1960's is indicative of an increase in fluxes of cold air from the north along the mid-Atlantic coast. This suggests that the mid-Atlantic area is more often positioned on the eastern flank of high-pressure cells. A displacement of lows to the east would be associated with this shift in the high-pressure system.

5. Conclusions and discussion

Results of this study indicate that a major component of climate change in the 1900's can be isolated by a single eigenvector, the second eigenvector of 5-day mean pressure. This eigenvector and only this eigenvector contained a statistically significant secular trend. The general variation of weightings on eigenvector 2 coincide with variations of circulation indices previously reported by Lamb (1965, 1966). The spatial form of this eigenvector is interpreted to represent an increase of high-latitude blocking, consistent with Lamb's (1966) data indicating a recent decrease in the strength of major zonal wind streams.

Empirical relationships calculated in this paper suggest an important coupling between large-scale circulation patterns and synoptic-scale atmospheric motions. Some effects of the apparent decrease in zonality of the general circulation are an offshore displacement of the mean storm track, a tendency for two modal positions of storm tracks off the east coast, rather than one, and an apparent increase in storm frequency. This apparent increase in storm frequency may, in fact, be only another manifestation of offshore displacement of the mean storm track since only storms moving offshore along the east coast were sampled in this study. It is important to note here that, although eigenvectors 3 and 4 exhibit variations from their means for lengths of time up to decades, the expected long-term secular variation of storms is associated entirely with the secular variation in eigenvector 2.

Since extratropical storms are primary sources for waves and storm surges along the mid-Atlantic coast in winter, variations in storm climate should result in related changes in the wave and surge climate. Results of Bosserman and Dolan (1968) indicate that wave-height recurrence intervals greater than one year are most affected by waves due to extratropical storms which enter the grid area used in the present study through line segment 5. Hence even though the present study does not support secular variations in storm climate as dramatic as those documented by Mather *et al.* (1964), the indicated 15% increase in these storms from the 1920's to the 1960's could be especially significant in terms of human impact. The importance of winter extratropical storms in terms of extremes of waves and surges accentuates the need for increased knowledge of wave and surge climates along coasts in the United States.

Table 3. Estimated frequency of storm types from Eq. (7) for decades in the 1900's.* The units are number of storms (of a particular type) per 5-day period.

Storm types	Decades 1900's	1910's	1920's	1930's	1940's	1950's	1960's
1	0.042	0.041	0.038	0.042	0.042	0.044	0.047
2	0.056	0.061	0.058	0.065	0.061	0.065	0.069
3	0.048	0.049	0.050	0.050	0.047	0.049	0.050
4	0.042	0.046	0.048	0.048	0.045	0.044	0.044
5	0.066	0.059	0.055	0.055	0.057	0.062	0.063
6	0.038	0.043	0.041	0.045	0.040	0.041	0.045
7	0.079	0.080	0.076	0.081	0.077	0.080	0.087
a-b-c	0.012	0.010	0.010	0.010	0.010	0.010	0.011
d-g	0.016	0.016	0.014	0.016	0.015	0.017	0.018
e-h	0.005	0.004	0.005	0.005	0.004	0.005	0.005
f-i	0.025	0.024	0.023	0.023	0.023	0.024	0.024
j	0.011	0.011	0.011	0.009	0.011	0.009	0.008
Total	0.440	0.444	0.429	0.449	0.432	0.450	0.471

* 1899 is included within the 1900's decade. 1970 is included within the 1960's decade. The frequencies for the 1930's are based on data for 1930–38. The frequencies for the 1940's are based on data for 1947–49.

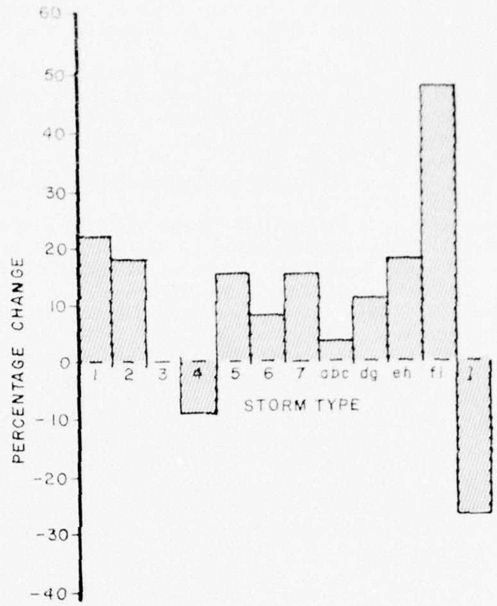


Fig. 7. Percentage change from the decade of the 1920's to the decade of the 1960's in the number of storms of each type defined by the grid in Fig. 4.

6. Summary

The primary purpose of this paper has been to investigate secular variations in the tracks and frequencies of extratropical storms along the mid-Atlantic coast. A principal-component analysis was used to establish an objective specification of patterns of 5-day mean surface pressure. Storm-track data were collected and assembled within categories of 5-day mean pressure. Storm frequencies and conditional probabilities of storm-track locations were derived as functions of large-scale categories. Using these relationships, storm-type probabilities were estimated for decades in the 1900's. The results indicate that recent changes in large-scale circulation are statistically significant and have produced related variations in the tracks and frequencies of synoptic-scale weather systems.

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13. ABSTRACT

An increase in storm damage along the east coast of the United States coincides with secular variations of the general circulation documented by several recent investigations. To determine the coupling between large-scale circulation patterns and extratropical storms along the mid-Atlantic coast, a principal-component analysis is used to characterize patterns of 5-day mean surface pressure and, within objective categories of these patterns, conditional probabilities of storm occurrences are calculated. Based on this probabilistic coupling, secular variations in frequencies of surface pressure patterns are used to estimate secular variations in mid-Atlantic storm climate. The results suggest that a significant trend has occurred in large-scale circulation. Physical interpretation of this change suggests an increase in the frequency of high-latitude blocking. Associated recent secular changes in storm climate are 1) an offshore displacement of the mean storm track; 2) an increase in the number of storms moving offshore; and 3) a tendency toward two modes, rather than one, of storm tracks along the mid-Atlantic coast. Since such changes alter the frequency of extreme wave and surge conditions along the coast, the consequences are highly significant in terms of human impact. (U)

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STORM WAVE CLIMATES AT CAPE HATTERAS, NORTH CAROLINA: RECENT SECULAR VARIATIONS

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Storm Wave Climates at Cape Hatteras, North Carolina: Recent Secular Variations

Bruce P. Hayden

Storm Wave Climates at Cape Hatteras, North Carolina: Recent Secular Variations

Abstract. *Mid-Atlantic coastal wave climates have undergone significant change within the last three decades. The duration and frequency of storms generating high waves and the length of the winter storm wave season have increased. These changes may, in part, account for the observed trend in shoreline erosion along the east coast of the United States.*

The U.S. Army Corps of Engineers has assigned more than 86 percent of the shoreline along the Atlantic coast of the United States to the categories of erosion or critical erosion (*1*). Numerous engineering measures have been implemented along the mid-Atlantic to check the continuing recession of the shoreline. This erosional trend has been attributed to a variety of factors including (i) the current sea level rise; (*ii*) the reduced supply of new sands from inland sources; (iii) human activites that alter the coastal geomorphology; and (iv) a lower average central pres-

sure of damaging storms (*2*). Previously unrecognized secular variations in storm wave climates are reported here as yet another important factor contributing to the coastal erosion.

Using the Bretschneider method, I have hindcasted the number of occurrences and the duration of storm waves at Cape Hatteras, North Carolina, for each of seven deep-water significant wave-height categories: 5.1 to 8.0 feet (1.6 to 2.4 m); 8.1 to 11.0 feet (2.5 to 3.4 m); 11.1 to 14.0 feet (3.4 to 4.3 m); 14.1 to 17.0 feet (4.3 to 5.2 m); 17.1 to 20.0 feet (5.2 to 6.1 m); 20.1 to 23.0 feet (6.1 to 7.0 m); and 23.1 to 32 feet (7.0 to 9.8 m) (*3*). I chose 5.1 feet as the lowest limit because smaller waves do not erode the barrier-island dune face along the coast of North Carolina.

Fetch length was estimated from U.S. Weather Bureau 12- and 24-hour synoptic weather charts. I obtained wind speed over the fetch area from records of the Cape Hatteras Weather Station, from published logs of ships at sea, or by estimating wind speed from isobaric spacings. There were 1009 extratropical storms from July 1942 through June 1974 which generated deep-water waves in excess of 5 feet.

Figure 1 summarizes the monthly occurrence over the last 30 years of storms generating deep-water significant wave heights equal to or greater than 5 feet. From 1943 to 1960, there was a winter maximum for storm occurrences in March. In the first half of the 1960's this maximum shifted from March to February and in the latter half of the 1960's to January; concurrently, from 1965 to 1970, there was a spring maximum in April.

During the 1940's there was a secondary maximum in January which shifted to December for the first half of the 1950's and to November for the second half of the 1950's. By the second half of the 1960's and into the 1970–1974 period, this secondary maximum is clearly evident in October even though it is not evident during the first half of the 1960's. This early season maximum is followed by a seasonal storm frequency minimum in the following month. These data show a general lengthening of the storm season over the last three decades, with the greatest changes occurring in the 1960's. The storm season increased by 4 months from 1942 to 1973, with duration defined as the time between the first and the last seasonal maxima.

In addition to a lengthening of the storm season, an increase in the frequency or duration of high waves also results in the dominance of erosion over deposition. Dolan and Vincent (*4*) found that 80 percent of the variance in the position of the Cape Hatteras shoreline from 1945 to 1969 was caused by deep-water waves in excess of 11 feet. In 1972 and 1973, during field studies at Cape Hatteras, I found that oceanic overwash was initiated only by deep-water waves of 11 feet or more. Accordingly, I have summarized the frequencies of wave events of 5 feet and greater and the frequencies and durations of wave events of 11 feet and greater for the 1942–1974 period (Table 1).

Table 1. Variations in storm wave frequency and magnitude since 1942; I, mean annual number of storms with waves greater than 5 feet; II, mean annual number of storms with waves greater than 11 feet; and III, yearly mean number of hours of waves greater than 11 feet.

Period	I	II	III
1942–1945	30.7	3.3	64.0
1945–1950	35.5	4.0	57.4
1950–1955	33.0	3.2	42.6
1955–1960	38.4	3.8	49.6
1960–1965	33.2	4.0	40.6
1965–1970	32.2	7.0	117.2
1970–1974	26.0	6.8	122.5

During the 1942–1965 period, 10.7 percent of the storm wave events recorded reached the 11-foot deep-water wave magnitude. From 1965 through 1974, 26.0 percent reached this same magnitude, a 2.43-fold increase. The probability of an 11-foot wave event increased 1.86 times during recent years (1965–1974) by comparison with the 1942–1965 period. In addition to the increased frequency of 11-foot storm wave events and a greater proportion of storms reaching this magnitude, the average annual duration of such storm waves increased over the same period. From 1942 to 1965 the average annual duration of 11-foot waves was 50.8 hours. Since 1965 an average annual duration of 119.9 hours has been recorded. This difference amounts to a 136 percent increase in the total annual duration.

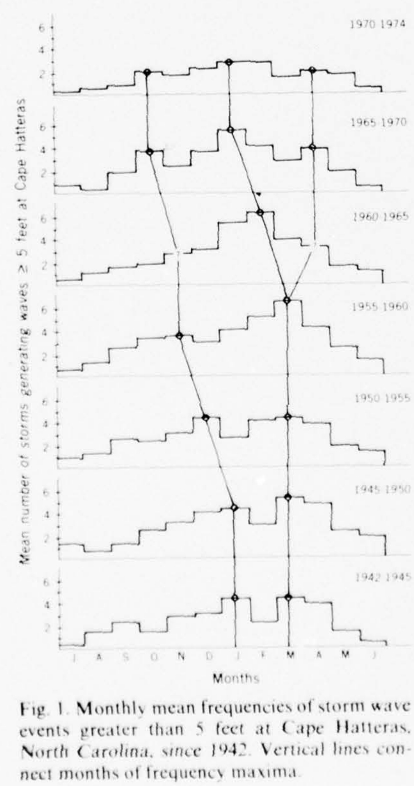

Fig. 1. Monthly mean frequencies of storm wave events greater than 5 feet at Cape Hatteras, North Carolina, since 1942. Vertical lines connect months of frequency maxima.

The most recent period studied (July 1970 through June 1974) is the stormiest on record for Cape Hatteras in spite of the exceptionally calm year from July 1973 to June 1974. Excluding this unusually calm year, the mean annual duration of waves over 11 feet totals 149 hours, nearly three times that observed for the years before 1965. So far during the 1970's, fewer storms than before have generated waves greater than 5 feet; however, a large percentage of those storms that have occurred have had waves higher than 11 feet and were of long duration.

The secular changes in the length of the storm season, the frequency of large storm waves, and the durations of high waves are consistent with the observed trends in shoreline erosion. Since beach sands are transported from the beach to offshore areas during the winter and from offshore to the beaches in the summer, the observed lengthening of the winter storm season is consistent with a deficit in the annual budget of beach sand. The recent higher frequencies and longer durations of high waves would also cause an increase in the net transport of sands from the beaches since waves of larger magnitude are the principal agents in the offshore transport of beach sands.

Whether or not the observed secular changes in the storm wave climate of Cape Hatteras are the result of general worldwide climatic changes recently reported (*5*) remains unresolved for the present. However, these documented changes at Cape Hatteras have raised important questions regarding the impact of climatic changes in general and specifically about their impact on shoreline stability.

Important questions are also raised concerning associated changes in the circumpolar vortex of the atmosphere and the positioning of ridge-and-trough systems in the North American sector. Similar studies for the west coast of the United States would contribute to the resolution of these questions.

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13. ABSTRACT

Mid-Atlantic coastal wave climates have undergone significant change within the last three decades. The duration and frequency of storms generating high waves and the length of the winter storm wave season have increased. These changes may, in part, account for the observed trend in shoreline erosion along the east coast of the United States. (U)

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MULTIVARIATE AND SPECTRAL ANALYSES OF SOME SEASONAL ASPECTS OF COASTAL WAVE CLIMATES

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ABSTRACT

Using surf height and direction statistics collected during the Cooperative Surf Observation Program (COSOP) for Virginia Beach, Virginia seasonal transitions in wind wave climates along the U.S. Atlantic coast are identified. The summer surf regime begins around May 6th and ends about August 10th. The following Fall storm season runs through October 20. In addition, spectral analyses of the daily weightings of the principal component functions are found to exhibit several periodicities. Periods commonly found include 6.5, 8, 10-12, 15-17, 27-30, and 43-45 days and are noteworthy in that similar periods have been reported for various atmospheric phenomena. The conclusion that a structured seasonal chronology of coastal wave climates exists supports the meteorological literature on singularities and natural seasons.

1. Introduction

Ocean surface wind waves and the associated generative processes have been extensively investigated; less studied are the temporal and spatial variations of wind waves in the coastal zone. With the exception of statistical summaries, and a few hindcasted storm records, the science of coastal wave climatology hardly exists at all. In part this deficiency resulted from long-held beliefs that there is no systematic organization within the annual cycle. Evidence is presented here that there is.

In this paper methods are developed for using the eigenvectors of the correlation matrices of 3-day running means of surf heights and directions. The resulting empirical orthogonal functions, and the time series of their weightings, were analyzed for the purpose of specifying the seasonal chronology of coastal wave climates. Spectral analyses of time series of the eigenvector weightings are used to identify recurrent events of the wave climate record.

2. Background

With the exception of a recent paper by one of the authors (Hayden, 1976), the concept of a precise seasonal structure in coastal wave climates as presented in this paper does not have precedence in the literature. Coastal investigators in general have not recognized a seasonal wave climate structure shorter than the broad winter/summer cycle. The concept of a seasonal structure, however, is not without theoretical substance. The relationship between wind fields and wave generation is well recognized and seasonal chronologies of various aspects of the general circulation of the atmosphere are recurrently reported on in the literature: Talman, C.F. (1919), Brooks, C.E.P. (1946), Ehrlich, A. (1954), Bryson, R.A. and Lahey, J.F. (1958), Caskey, J.E. (1963), Bradka, J. (1966), Namias, J. (1968), Wahl, E. (1972), and Lamb, H.H. (1973).

Namias (1968) demonstrated the existence of a late-November singularity which was in part characterized by frequent cyclogenesis off the mid-Atlantic coast. The Fall season transition of the southward shift of the polar front in mid-October (Bryson and Lahey 1958) and the concommitant rise in the magnitude of the Wadsworth storminess index should give rise to increased storm wave activity. That natural climatological seasons are definable in terms of synoptic characteristics is demonstrated by Lamb (1973). The hypothesis here is that there is a commensurate seasonal structure in coastal wind wave climates.

3. COSOP Data

At 26 Coast Guard stations located around the conterminous United States visual observations of daily surf characteristics were collected between the mid-1950's and 1970. This program of data collection is known as the CERC-USCG Cooperative Surf Observation Program (COSOP) and was begun in 1954 by the Beach Erosion Board of the U.S. Army Corps of Engineers. COSOP data consists of visual estimates of surf height, direction and period. Observation frequency is 6 times daily, visibility permitting. Heights are estimated in 1 ft. intervals and directions are assigned one point of the standard 8 point compass. While most of the illustrative materials used here are for the Virginia Beach, Virginia, Coast Guard station record, similar analyses have been completed for Moose Peak, Maine; Hampton Beach, New Hampshire; Point Judith, Rhode Island; Atlantic City, New Jersey; Ocean City, Maryland; Hillsboro Inlet, Florida; Pensacola, Florida; St. Joe, Florida; Point Arguello, California; Point Arenas, California and Cape Flattery, Washington.

In the present study 15 year mean observational frequencies in wave height and directions classes for each calendar day were calculated and subsequently smoothed using a three-day running mean. The resulting 365 day climatological time series of frequencies were analyzed.

4. Analysis

The surf height and direction frequencies of the COSOP data constitutes a multiple variable information set. As such systematic organizations among the variables may be specified by principal component analysis. In terms of least square error, principal-component analysis provides an optimal means of objectively specifying patterns in data fields (Lorenz, 1956; Gilman, 1957, Kutzbach, 1967 and Resio and Hayden, 1975). Basically the analysis transforms a set of intercorrelated variates into a new coordinate system with inherent statistical properties. The axes in the new coordinate system are linear combinations of the original variates and are mutually orthogonal.

The correlation matrix from which eigenvectors were calculated consisted of N observations, the number of days in the time series (365), on M variables, the sum of the number of surf height and direction classes. In order to distinguish fair-weather from storm wave climates three separate subsets of the data (the Virginia Beach, Virginia, COSOP record) were analyzed. Subset 1 consisted of all wave observations, subset 2 - surf less than 4 ft. and subset 3 - surf greater than 4 ft. Because the number of variables, M, is relatively small, only an equal number of eigenvectors may be calculated. In this study only the

first eigenvictors are used as interpretation bases. The time series of weighting on the eigenvectors calculated were plotted and examined. Because periodicities were apparent in these time series plots, power spectral analyses were conducted to specify the recurrent periods.

5. The Eigenvectors

The variable multipliers for the first eigenvectors for the all waves, fair-weather, and storm-waves data subsets, are given in Table 1. The first eigenvector for all waves distinguishes low surf from the southeast direction (positive eigenvector weight) from higher surf from the northeast and east (negative eigenvector weighting). This eigenvector may be referred to as a general fair weather/foul weather function.

The first eigenvectors calculated for surf less than 4 ft. and surf greater than 4 ft. are also given in Table 1. The general form of the low surf eigenvector does not differ significantly than that calculated using the all waves subset of the data.

The first eigenvector for the high surf data subset is heavily weighted on the surf height variables while weightings on the direction components is modest. The occurrence of high waves from southeast and east, implies that the causal storms track offshore south of Virginia

TABLE 1

Eigenvector 1 Multipliers in Tabular Form

Variable	All Waves	Waves $\leq$ 4'	Waves $\geq$ 4'
NE	-.2543	-.4328	-.0744
E	-.2120	-.2780	.1545
SE	.3284	.5120	.0803
0-1'	.3029	.2630	--------
1-2'	.2321	.2592	--------
2-3'	-.3861	-.4154	--------
3-4'	-.4598	-.4053	--------
4-5'	-.4328	--------	.4568
5-6'	-.2585	--------	.5239
6-7'	-.1375	--------	.5334
7'+	-.0584	--------	.4433

Beach and move northeastward. The form of this high surf function differs significantly from the high waves portion of the all waves eigenvector. Under the all waves analysis high waves are associated with northeast and east surf directions. High waves are present at Virginia Beach when a storm tracks offshore near to the north of Virginia Beach. With this type of storm movement high waves from the southeast are not expected.

6. Seasonal Chronology

Plots of the eigenvector weightings for each observation day constitutes a climatological time series of the surf conditions at Virginia Beach (Fig. 1). It is immediately apparent that curves A and B, all waves and waves $\leq$ 4 ft. respectively, are nearly identical. This attribute results from the preponderance of low surf observations. If the all-waves eigenvector is a general fair/foul weather function, then this attribute characterizes the conditions of the summer-winter transition. Summer apparently begins about May 6th and ends August 10th. The summer surf regime is southeast, waves generally less than 2 ft. These waves are classed as swell and their origin would be attributed to the subtropical anticyclone of the North Atlantic. Around August 10th higher waves out of the northeast and east begin to dominate. These

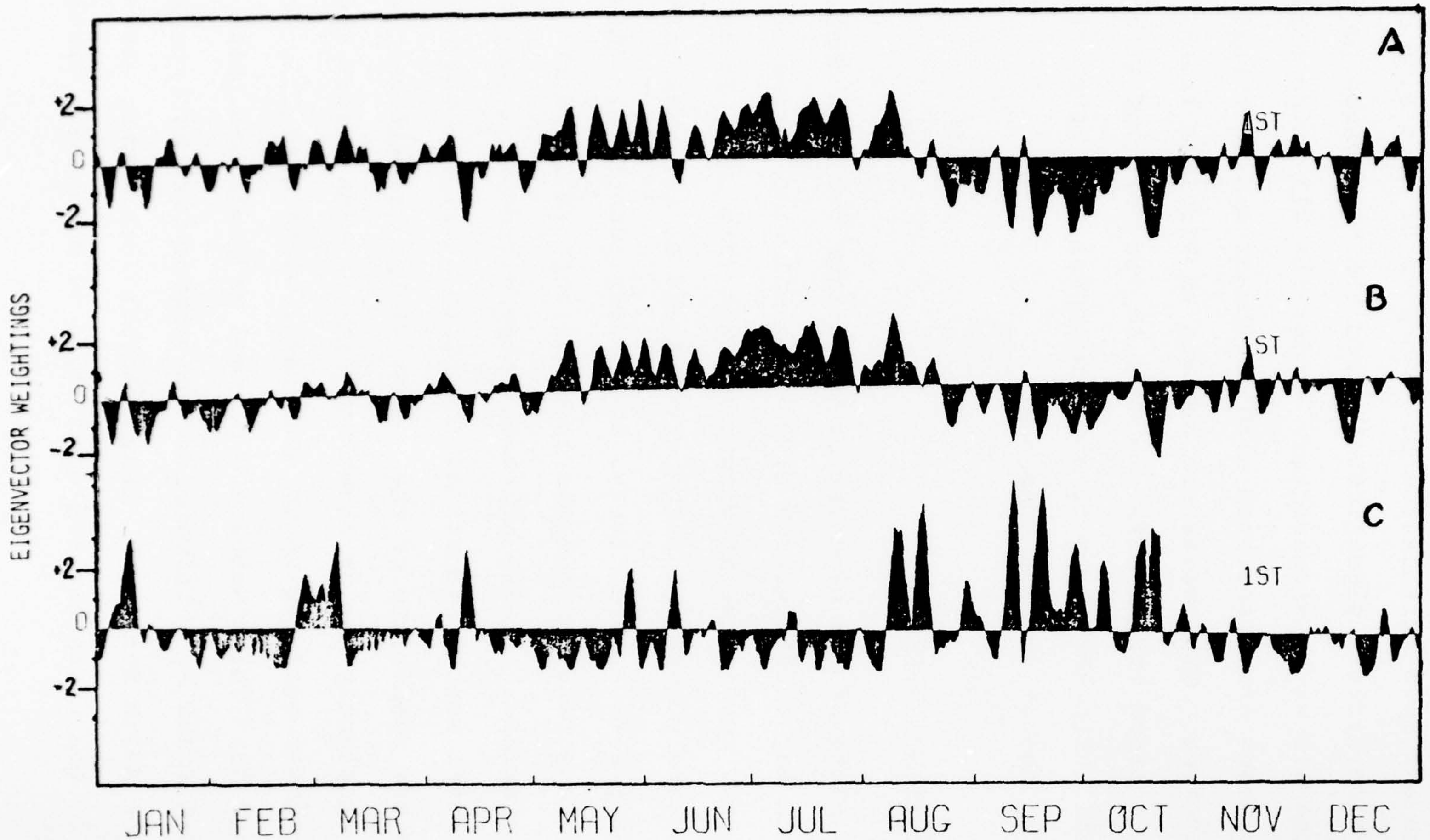

FIGURE 1. TIME SERIES OF EIGENVECTOR WEIGHTINGS: A = ALL WAVES; B = WAVES $\leq 4'$; C = WAVES $\geq 4'$.

waves are probably the result of cyclones and fronts to the east and north of Virginia Beach.

The chronology for the eigenvector of waves in excess of four feet as mentioned earlier is consistent with southerly storm tracks first yielding southeast surf, then east surf and finally northeast surf. These storms begin around the 10th of August and may include hurricanes; however, hindcast studies of storm wave conditions at Cape Hatteras clearly indicate that each of these peaks (Fig. 1 curve C) can be attributed to extra-tropical cyclones. Fall (Aug. 10 - Oct. 20) is clearly the major season for these storms. It is quite probable that the recurring southward excursions of the zonal westerlies reported by Wahl (1972) and thus the southward displacement polar front during this period accounts for the frequent and recurrent southerly tracking storms.

At the end of February and beginning of March there is another period of high weighting on the high surf eigenvector. More southerly storms at this time are also expected because of the tendency for the primary mid-winter low index (southward westerlies) to occur around these dates. Hindcast studies for Cape Hatteras indicate that 80% of the most severe winter storms occur between mid-February and mid-March. Thus this high surf eigenvector may characterize the climatology of the most damaging type of Atlantic coastal storm. In any case the con-

cept that storms occur randomly in time with a preference for the winter storm season should be reconsidered.

7. Power Spectra

Because the time series of eigenvector weightings (Fig. 1) appeared to exhibit some periodicities, spectral analyses were performed (Fig. 2 and 3). Periods of 43-45 days, 27-30, 15-17, 10-12, 8, and 6.5 days were evident in the Virginia Beach record of waves in excess of 4 ft. While the assignment of causality to each of these periodicities is not within the scope of this investigation several of these periods have been reported in the meteorological literature (Table 2). While the trend components of the time series were not filtered and to date no confidence limits have been calculated, we are convinced that several periodicities exist and are real. Confidence is bolstered in this case because several of these periodicities were also evident in similiar analyses for Moose Peak on the Gulf of Maine, Hillsboro Inlet, Florida and for Cape Flattery, Washington (Fig. 3).

8. Conclusions

Definition of the onset and close of atmospheric seasons has been debated and remains controversial among

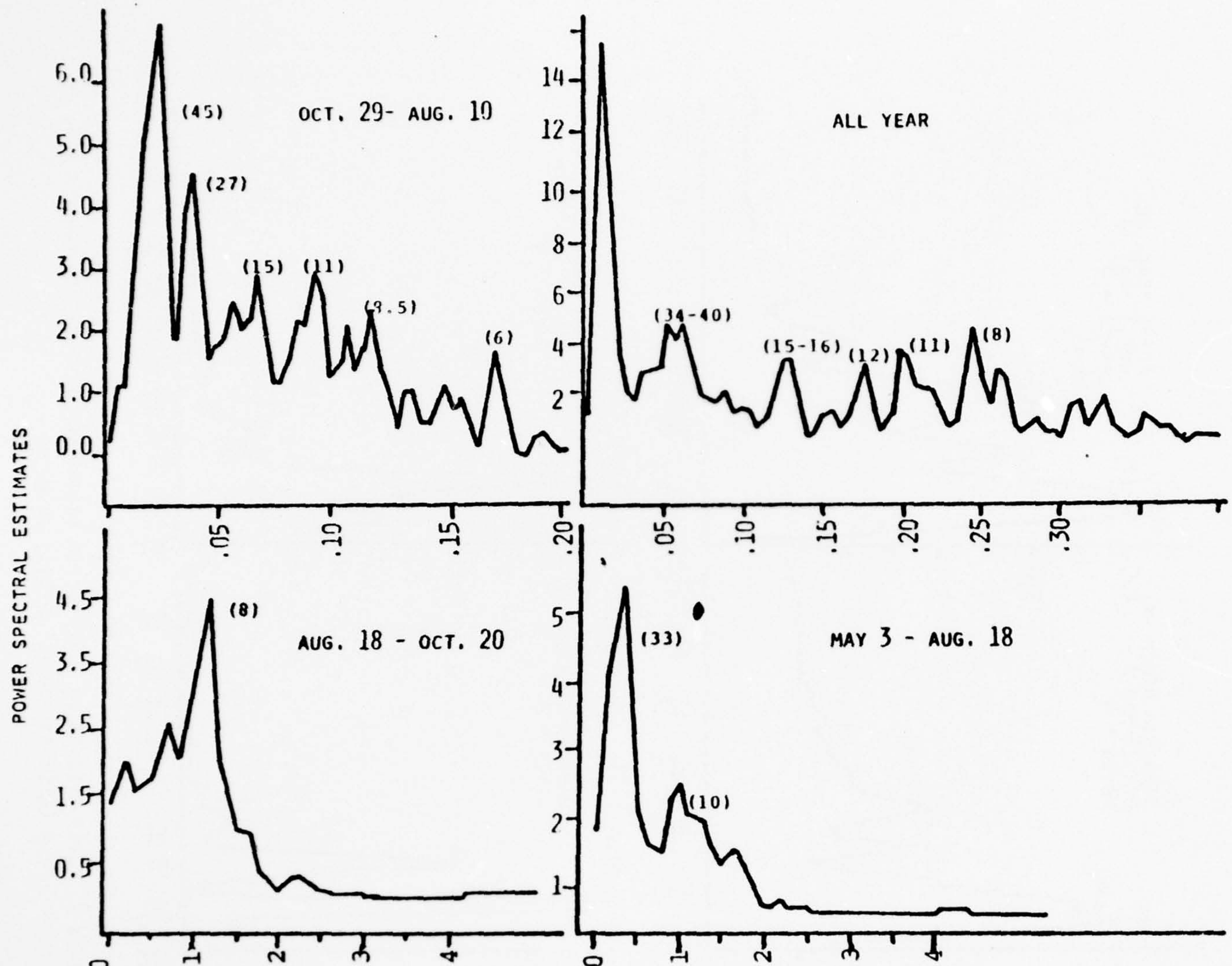

FIGURE 2. POWER SPECTRA OF VIRGINIA BEACH (WAVES = 4') EIGENVECTOR WEIGHTINGS (PERIOD IN DAYS)

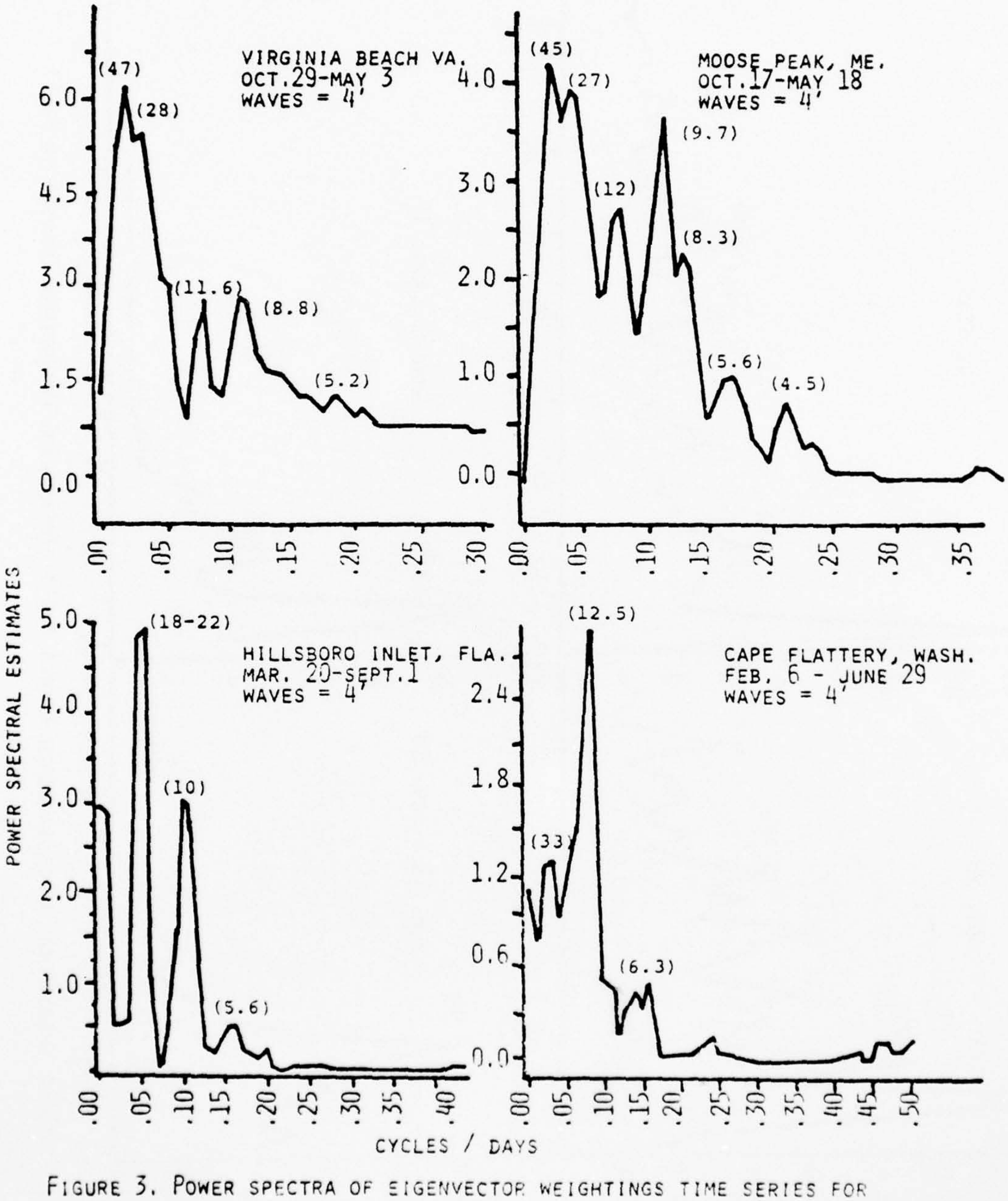

FIGURE 3. POWER SPECTRA OF EIGENVECTOR WEIGHTINGS TIME SERIES FOR FOUR COSOP STATIONS. (PERIOD IN DAYS)

TABLE 2

Meteorlogical Periodicities

Parameter	Mode	Author
Grosswetter duration	5.5 days	Baur 1936
Pressure in tropics	5 days	Madden and Julian 1972
Jet stream configurations	6.4 days	Kletter 1959, 1962
Jet stream configurations	8 days	Kletter 1959, 1962
Tropospheric u, v wind components	10-15 days	Wallace and Chang 1969
North Atlantic trade wind surges	15 days	Krisnamurti et al. 1973, 1975
Precipitation	27-30 days	Brier and Bradley 1964 Visvanthan 1966
Eastern Pacific anticyclone latitude	27-30 days	Bryson 1948
Pressure, vapor pressure in the tropics	40-50 days	Madden and Julian 1972

atmospheric scientists. There has been no equivalent debate on the questions of natural seasons in shallow water hydrodynamical conditions. Our studies at other Atlantic and Pacific coast COSOP stations indicate that the dates of season beginnings and endings are geographically synchronous. This suggests a global scale phenomena. That the observed periodicity should be present in climatological time series of 15-year means further suggests that a structural seasonal organization must exist in the coastal wave environment. Should further studies confirm these findings then renewed interest in the causal atmospheric phenomena should result.

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Technical Report No. 18

JANUARY-THAW SINGULARITY AND WAVE CLIMATES ALONG THE EASTERN COAST OF THE USA

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January-thaw singularity and wave climates along the Eastern coast of the USA

METEOROLOGICAL singularities—recurrent weather phenomena at or near specific calendar dates[1]—have been reported throughout the Northern Hemisphere. Although not fully recognised as real phenomena by most meteorologists, singularities continue to merit the attention of some investigators. Although the general relationship between wind fields over open oceans and generation of waves by wind are well known, there are no reports in the literature on coastal wave climates and atmospheric singularities. I have observed that extreme frequencies of surf from directions more typical of the summer season occur at the time of the 'January-thaw' meteorological singularity (January 20–23). Here I present observations of wave climates from Florida to Rhode Island at the time of the January thaw.

Slocum[2] recorded an anomalous warm spell during January 20–23, between 1872 and 1921. Subsequently, Wahl[3] demonstrated the existence of the January thaw in New England for the period 1873–1952 and Frederick[4] reported on its extensive geographical distribution between 1927 and 1956. Wahl[3] also noted that at the time of the January thaw the ridge-and-trough positioning over eastern North America differed markedly from its positioning before afterwards; specifically, during the January thaw there is a high pressure cell off the east coast of the USA, and a trough runs through the midwest, whereas immediately following the thaw, the positions of the ridge and trough are reversed. Anticyclonic singularities have been reported for Europe (January 18–24) by Brooks[5] and Japan (January 24) by Maejima[6].

Duquet[7] has attributed the January thaw to an adjustment of the planetary circulation occurring in early or mid January. Wahl[8] has noted that the January thaw is most pronounced during low-index Januaries. Significant changes in the general circulation of the atmosphere at the time of the January thaw are well documented. These changes should appear as a singularity in coastal wave-climate statistics.

Surf-height and direction statistics for years falling within a period of general low index[9] were obtained from the Co-operative Surf Observation Program (COSOP) for Point Judith, Rhode Island (1957–1965); Atlantic City, New Jersey (1955–1964); Ocean City, Maryland (1955–1970); Virginia Beach, Virginia (1954–1969); Oak Island, North Carolina (1955–1965); and Hillsboro Inlet, Florida (1955–1965), (Table 1). Daily and 3-d running means of surf heights were examined but did not show any anomalous characteristics at the time of the singularity; however, at the time of the January-thaw singularity, the directions of approaching surf along the Atlantic coast are atypical of winter. The magnitude of the departure from winter conditions to surf conditions more typical of summer are demonstrated by the occurrence of extreme frequencies for various surf directions during the period of the singularity (Table 1). Although Wahl[3] has shown that the pressure field characteristic of the singularity is present on January 20, the maxima and minima of frequencies for each surf direction generally occur around January 23. This apparent lag may be attributable to the required time of wave generation and travel to the coast.

At Ocean City, Virginia Beach, and Hillsboro Inlet, surf from the south-east dominates. At Atlantic City extreme high frequencies of south surf occur, and at Point Judith surf from the south-west dominates. On Oak Island southerly and south-westerly surf dominates, and at Hillsboro Inlet north-easterly and south-easterly surf predominates. The hypothesis enunciated here is not supported only at Atlantic City where the 1% level-of-significance criterion was not met.

Duquet[7] has suggested that the January thaw is a mani-

Table 1 Daily and 3-day extremes of surf directions along the US eastern coast during the January thaw

Station and surf direction	January thaw: Daily extreme (Date) (%)	January thaw: 3-day mean extreme (mid-date)	January daily mean (%)	Month of daily maximum (% frequencies)	Month of daily minimum (% frequencies)
Point Judith, Rhode Island					
SE	38 (23rd)*	44 (22nd)*	55	May (65)	Sep (47)
SW	56 (22nd)§	43 (22nd)§	27	Aug (28)	May (19)
Atlantic City, New Jersey					
NE	0 (23rd)*	5 (23rd)	9	Dec (16)	Aug (1)
SE	57 (23rd)	63 (23rd)	77	Jul (84)	Mar (67)
S	19 (23rd)†	12 (23rd)†	3	May (7)	Oct (1)
Ocean City, Maryland					
NE	15 (21st)	18 (22nd)	23	Dec (30)	Jul (6)
E	28 (21st)	37 (22nd)	42	Dec (44)	Jul (26)
SE	52 (23rd)†	43 (22nd)†	30	Jul (58)	Dec (25)
Virginia Beach, Virginia					
NE	16 (23rd)*	26 (22nd)	39	Jan (39)	Jul (8)
SE	37 (23rd)†	28 (22nd)†	15	Jul (55)	Jan (15)
Oak Island, North Carolina					
SE	0 (22nd)	4 (21st)	5	May (13)	Jul (1)
S	74 (22nd)	69 (22nd)†	57	Oct (66)	Jun (52)
SW	26 (22nd)	25 (22nd)*	37	Apr (46)	Oct (24)
Hillsboro Inlet, Florida					
NE	0 (24th)*	5 (23rd)*	21	Jan (21)	Jul (1)
E	24 (23rd)‡	34 (23rd)	42	Apr (59)	Jan (42)
SE	47 (24th)§	42 (23rd)§	15	Jul (24)	Oct (7)

*Minimum value for month of January.
†Maximum value for month of January.
‡Minimum value for year.
§Maximum value for year.

festation of "an adjustment of the planetary circulation from what might be called an early winter stage to a late winter stage . . . " The statistics of south-easterly surf at Hillsboro Inlet support the season-transition concept. The period of October 1–January 20 is characterised by a mean frequency of south-easterly surf of about 9%. During the period January 20–end March, the mean frequency of surf from the south-east is 23%. Thus, the time progression of south-easterly surf at Hillsboro Inlet takes the form of step functions rather than of a monotonic sequence.

Coastal wave climates are traditionally viewed as a simple annual cycle between summer and winter conditions, and definition within the annual cycle is not generally recognised. If other atmospheric singularities are found to mark simultaneous changes in wave climates, then such information would have immediate application to coastal planning in general, and coastal engineering in particular. Further investigation of coastal wave climates should answer this question and may further clarify the many unanswered questions about atmospheric singularities.

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Extreme frequencies of surf from directions typical of the summer season occur at a time of the "January-thaw" meteorological singularity (January 20-23). Observations of wave climates from Florida to Rhode Island at the time of the January thaw support the concept of a physical relationship between coastal wave climates and atmospheric singularities. (U)

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